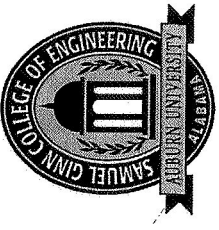


A One-Piece Lunar Regolith-Bag Garage Prototype

Shelter structures on the moon, even in early phases of exploration, should incorporate lunar materials as much as possible. We designed and constructed a prototype for a one-piece regolith-bag unpressurized garage concept, and, in parallel, we conducted a materials testing program to investigate six candidate fabrics to learn how they might perform in the lunar environment. In our concept, a lightweight fabric form is launched from Earth to be landed on the lunar surface and robotically filled with raw lunar regolith.

In the materials testing program, regolith-bag fabric candidates included: Vectran™, Nextel™, Gore PTFE Fabric™, Zylon™, Twaron™, and Nomex™. Tensile (including post radiation exposure), fold, abrasion, and hypervelocity impact testing were performed under ambient conditions, and, within our current means, we also performed these tests under cold and elevated temperatures. In some cases, lunar simulant (JSC-1) was used in conjunction with testing. Our ambition is to continuously refine our testing to reach lunar environmental conditions to the extent possible.

A series of preliminary structures were constructed during design of the final prototype. Design is based on the principles of the classic masonry arch. The prototype was constructed of Kevlar™ and filled with vermiculite (fairly close to the weight of lunar regolith on the moon). The structure is free-standing, but has not yet been load tested. Our plan for the future would be to construct higher fidelity mockups with each iteration, and to conduct appropriate tests of the structure.



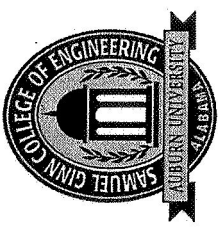
A One-Piece Lunar Regolith-Bag Garage Prototype

Space Resources Roundtable VIII
October 31, 2006

Gweneth A. Smithers, Mary K. Nehls, Mary A. Hovater, Steven W. Evans
NASA/Marshall Space Flight Center, Huntsville, Alabama

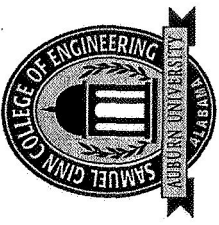
J. Scott Miller
Qualis Corporation/Marshall Space Flight Center, Huntsville, Alabama

Roy M. Broughton, Jr., David Beale, and Fatma Kilinc-Balci
Auburn University, Auburn, Alabama



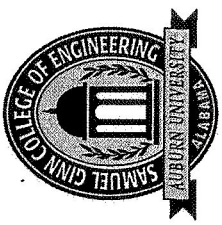
Goals

- To learn, through materials testing, which commercial fabric materials are best suited for use in construction of a one-piece regolith-bag form.
- To construct a “lunar garage” prototype from the one-piece regolith bag form filled with regolith, and big enough for a person to stand inside.



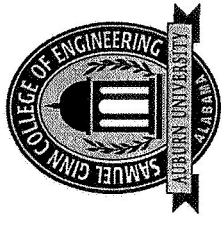
Candidate Fabric Materials

- 1. VectranTM - polyester liquid crystal polymer, (LCP)
- 2. NextelTM - aluminoborosilicate (ceramic)
- 3. Gore PTFETM - expanded polytetrafluoroethylene (PTFE)
- 4. NomexTM - meta-aramid fiber
- 5. TwaronTM - para-aramid fiber (used instead of KevlarTM - has similar chemistry);
- 6. ZylonTM - a rigid-rod polymer - poly (P-phenylene-2,6-benzobisoxazole), PBO.



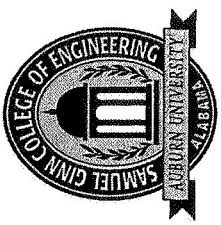
Fabric Parameters

Fabric	Weave	Denier	Const
Nextel	1/4 Satin	600/600	46/46
Nomex	Plain	200/200	54/54
GorePTFE	1/3 Satin	400/400	88/84
Twaron	Plain	500/500	48/46
Vectran	Plain	400/400	54/54
Zylon	Plain	500/500	30/30



Warp Yarn Strength

Fabric	Y str kN	Y str kN	Conv %
	Measured	Calc from Fab	
Nextel	0.0081	0.017	208
Nomex	0.0094	0.0084	89
Gore PTFE	0.0165	0.015	92
Twaron	0.0720	.044	61
Vectran	0.0840	.042	50
Zylon	0.1330	.089	66



Fabric Strength Testing

ASTM D-5035 strip test

Five fabric samples of each fabric

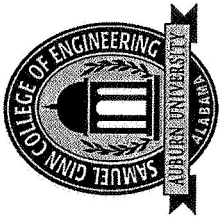
Jaw face is 2 inches square

6 in/min cross-head speed

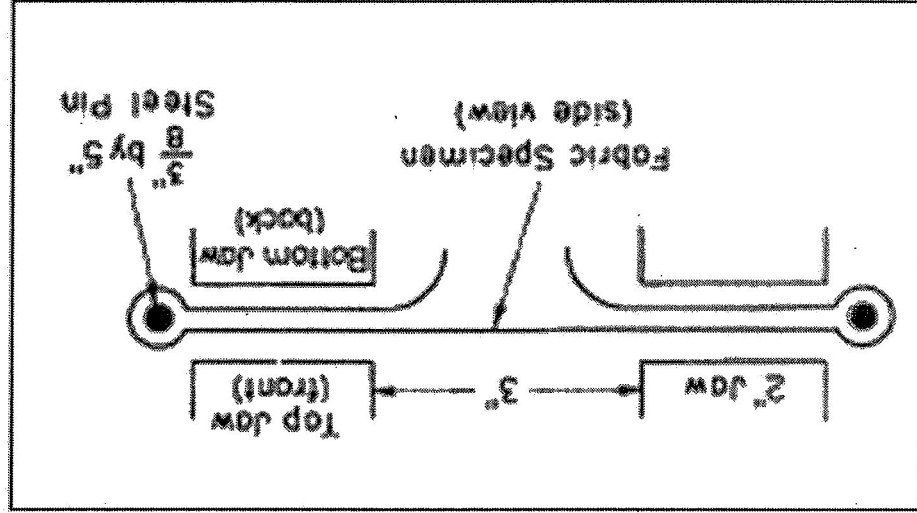
3 inches gage length, 2 inch width

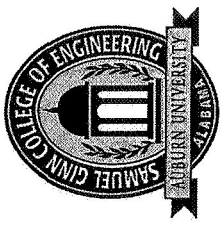
Manual clamps

Modified clamping geometry as needed



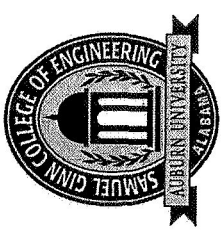
Test Setup





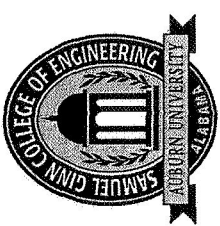
Fabric Strength

Fabric	kN/in		MPa	
	W	F	W	F
Nextel	0.804	0.745	679	673
Nomex	0.462	0.425	522	505
Gore PTFE	1.34	1.37	736	801
Twaron	2.06	4.52	1160	2589
Vectran	2.29	4.26	1308	2535
Zylon	2.66	3.77	2509	3553



Fabric Elongation

Fabric	Elongation	
	W	F
• Nextel	2.6	2.3
• Nomex	16.4	15.2
• Gore PTFE	17.1	10.6
• Twaron	14.1	6.6
• Vectran	19.6	8.9
• Zylon	8.0	6.4

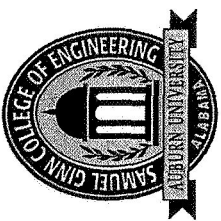


Fabric Testing Conclusion

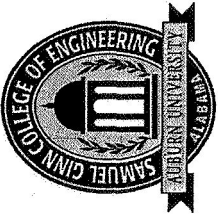
- For higher strength fabrics, the warp is stronger than the filling direction.
- For all fabrics, the warp has more elongation than the filling direction



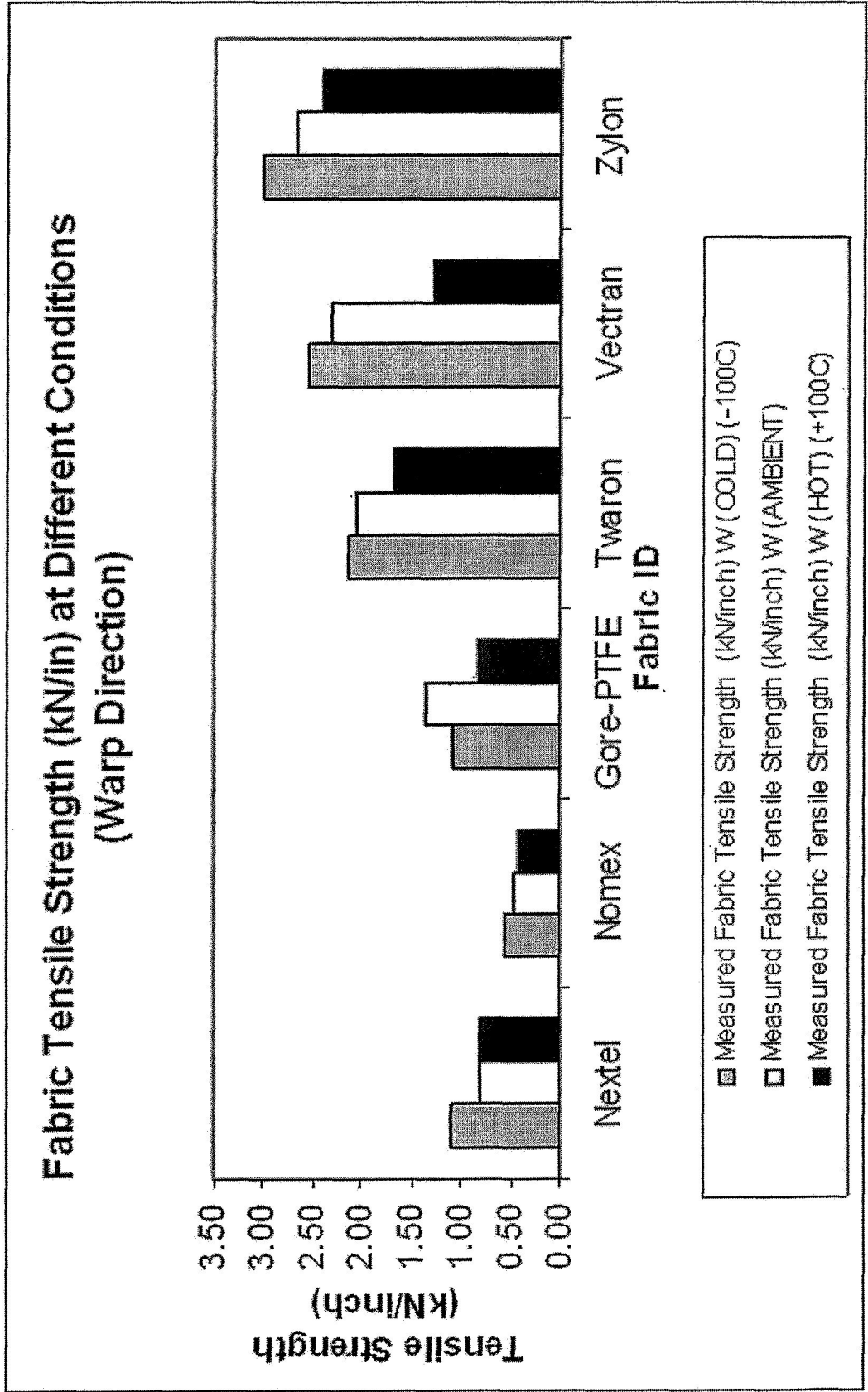
Fabric at Lunar Temperatures



- Tensile tests were performed on five samples of each fabric type according to ASTM D-5035.
- In an Instron Environmental Test Chamber model 3119 --
- Heated at 100 C (the chamber is an oven), and
- Cooled at -100 C (using the gas expelled from liquid N₂)

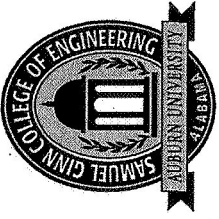


Fabric Strength at Different Temperatures

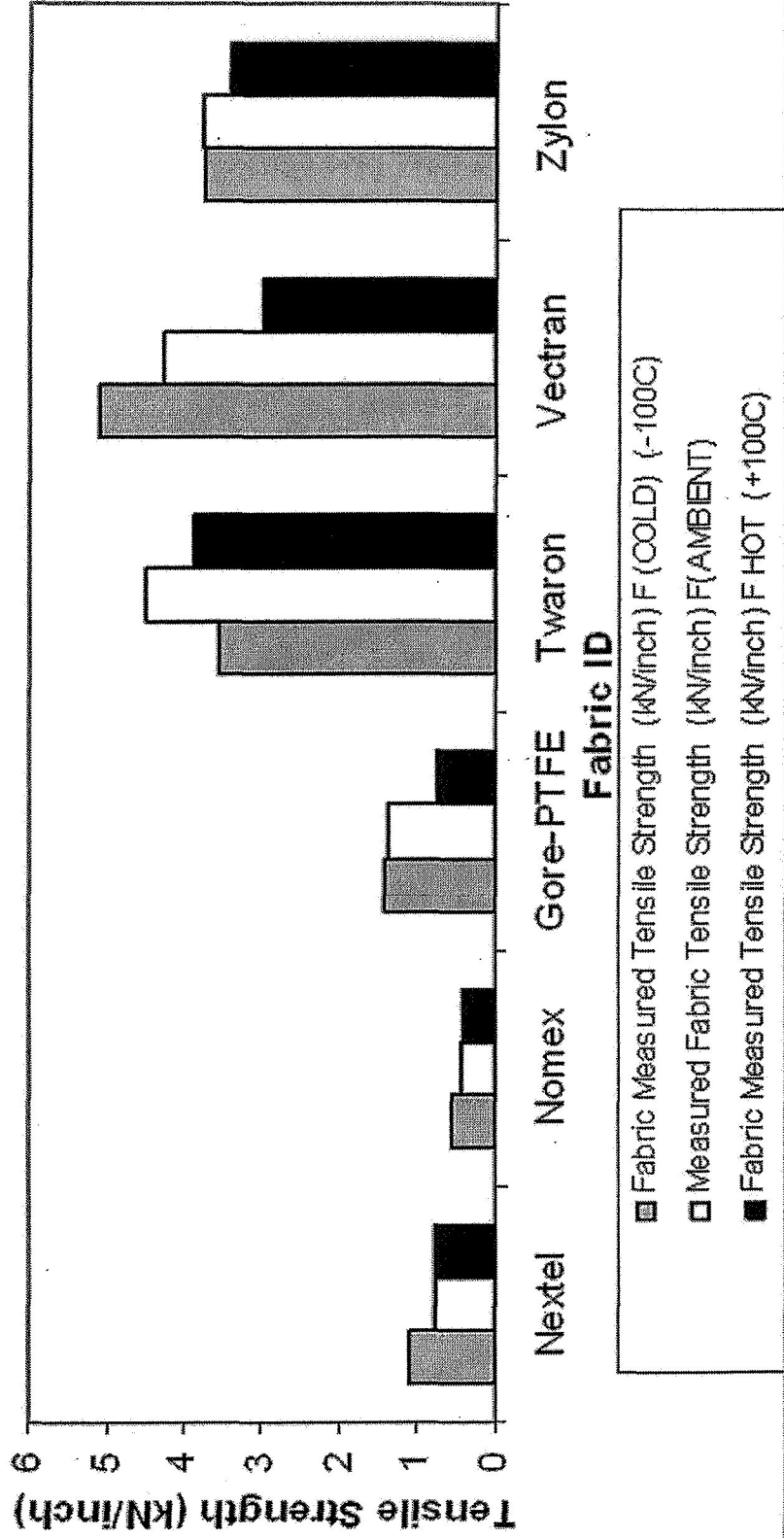




Fabric Strength at Different Temperatures

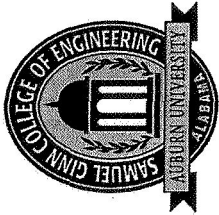


**Fabric Tensile Strength (kN/in) at Different Conditions
(Filling Direction)**

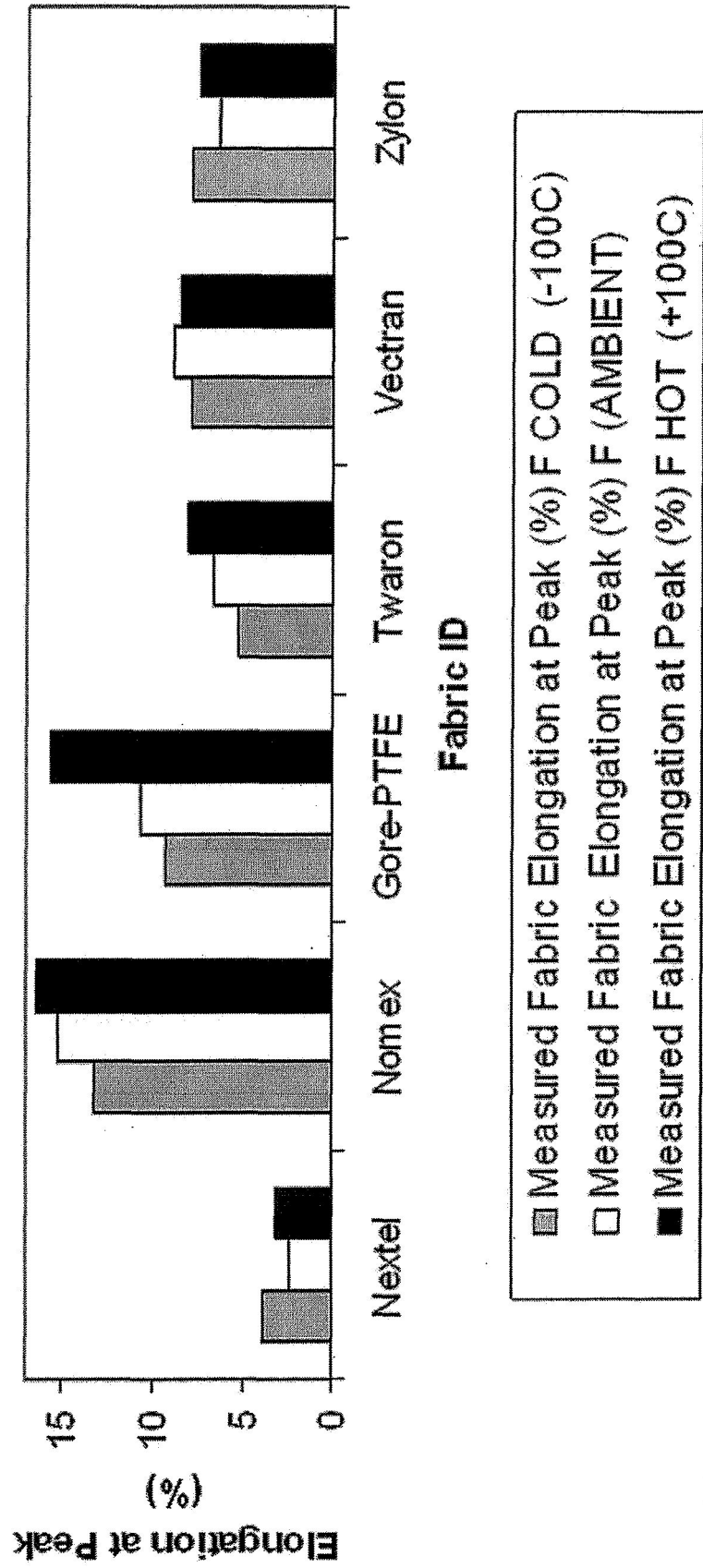


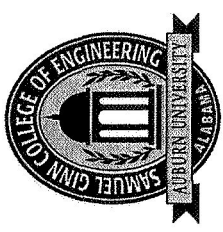


Fabric Elongation at Different Temperatures



**Fabric Elongation at Peak (%) at Different Conditions
(Filling Direction)**

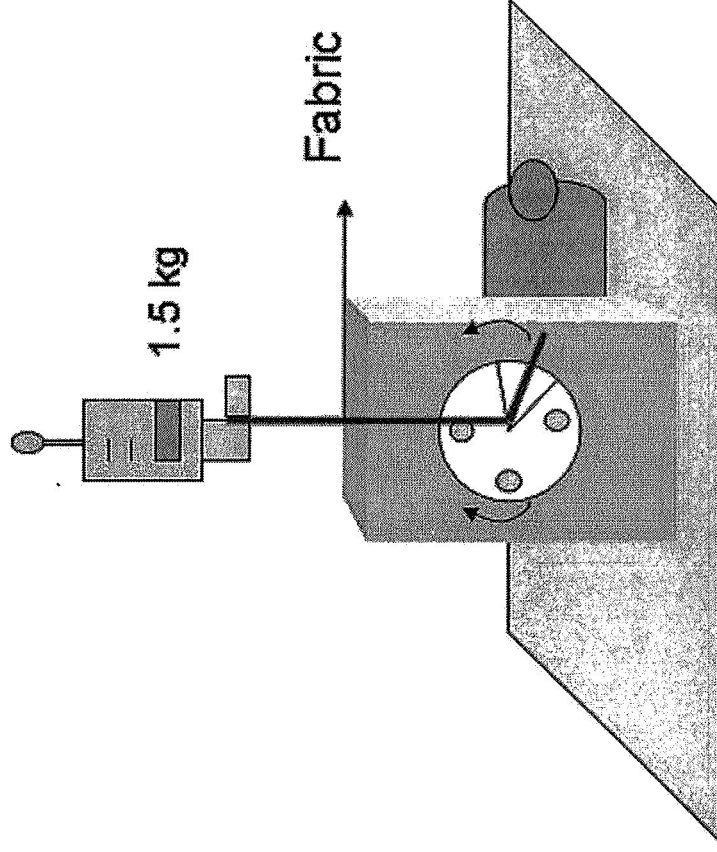




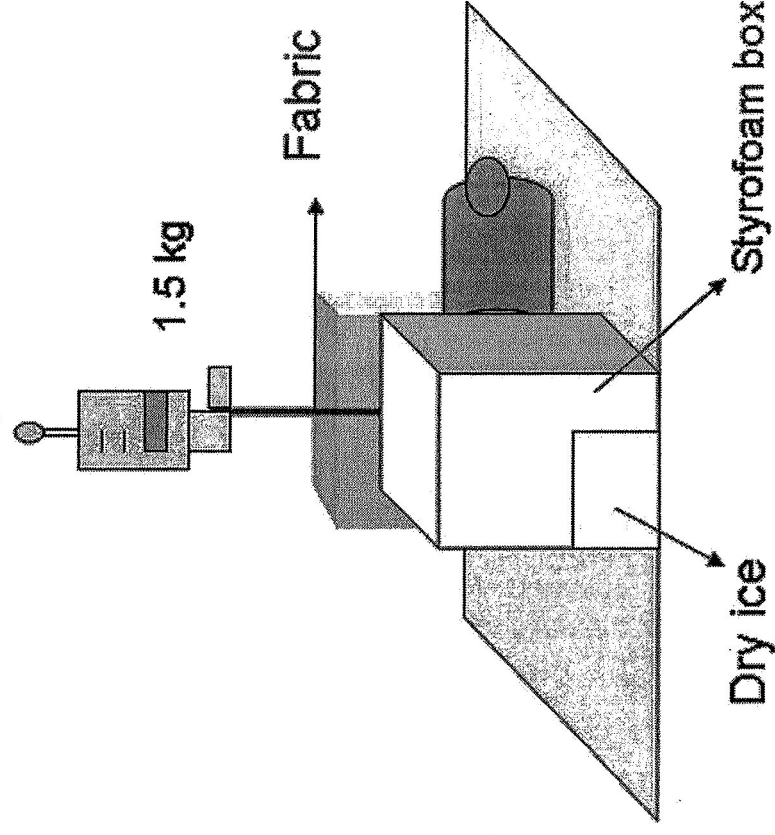
Fold Testing

- Three specimens were tested for each fabric at each temperature:
- ambient lab conditions,
- - 50 C and
- - 195 C.

Folding Test Device

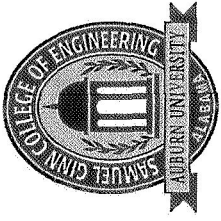


Folding test device before modification.

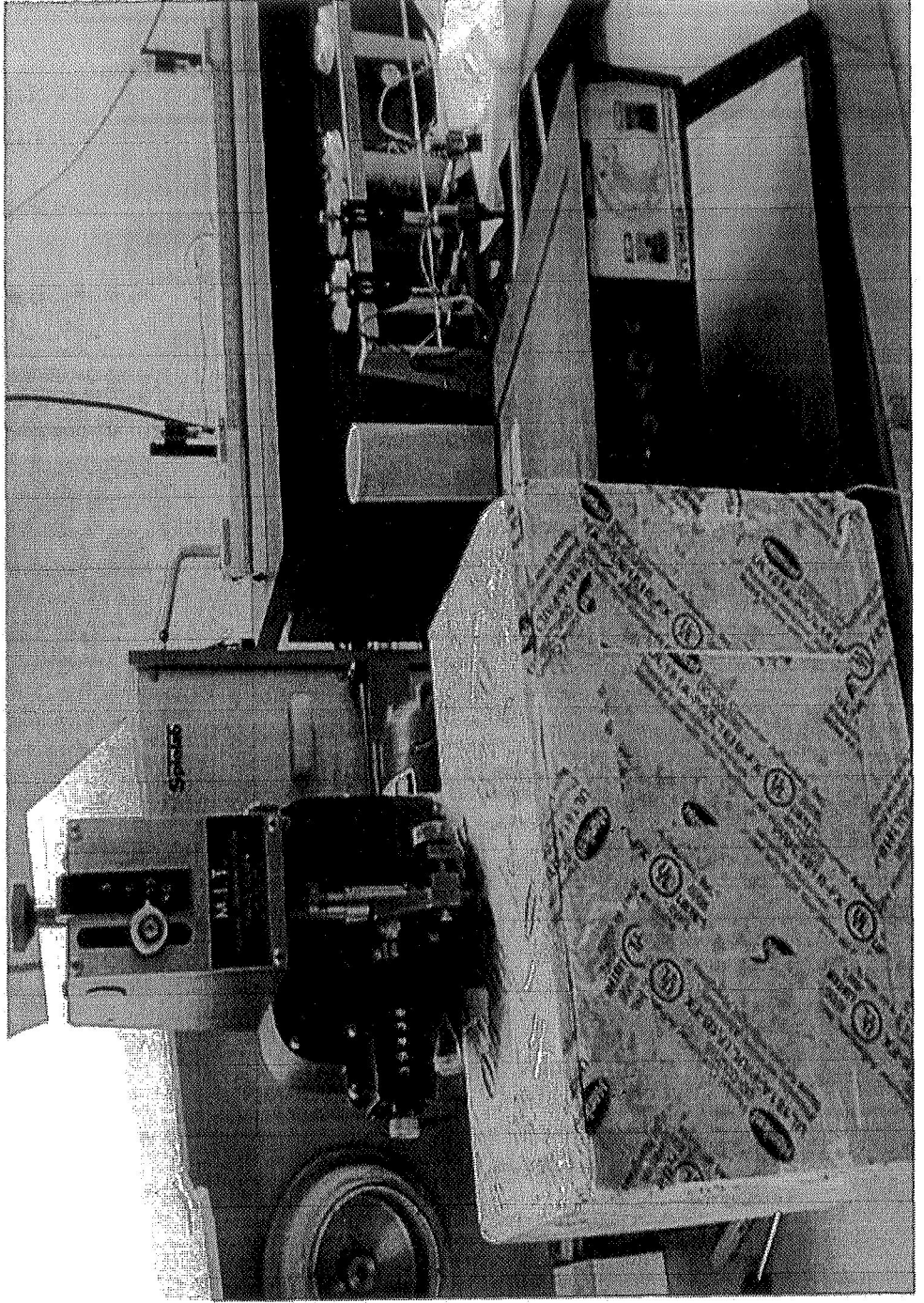


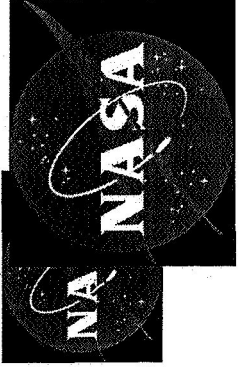
Folding test device after modification for cold temperature

Folding test performed in a box with dry ice at cold temperature.

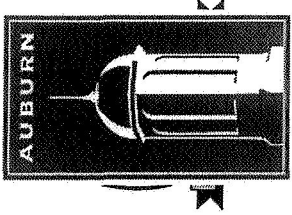


Folding Test Cold (-50C) with dry ice (sublimation temp: -78.5C)

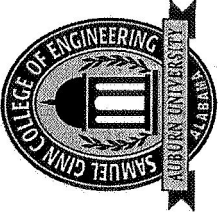




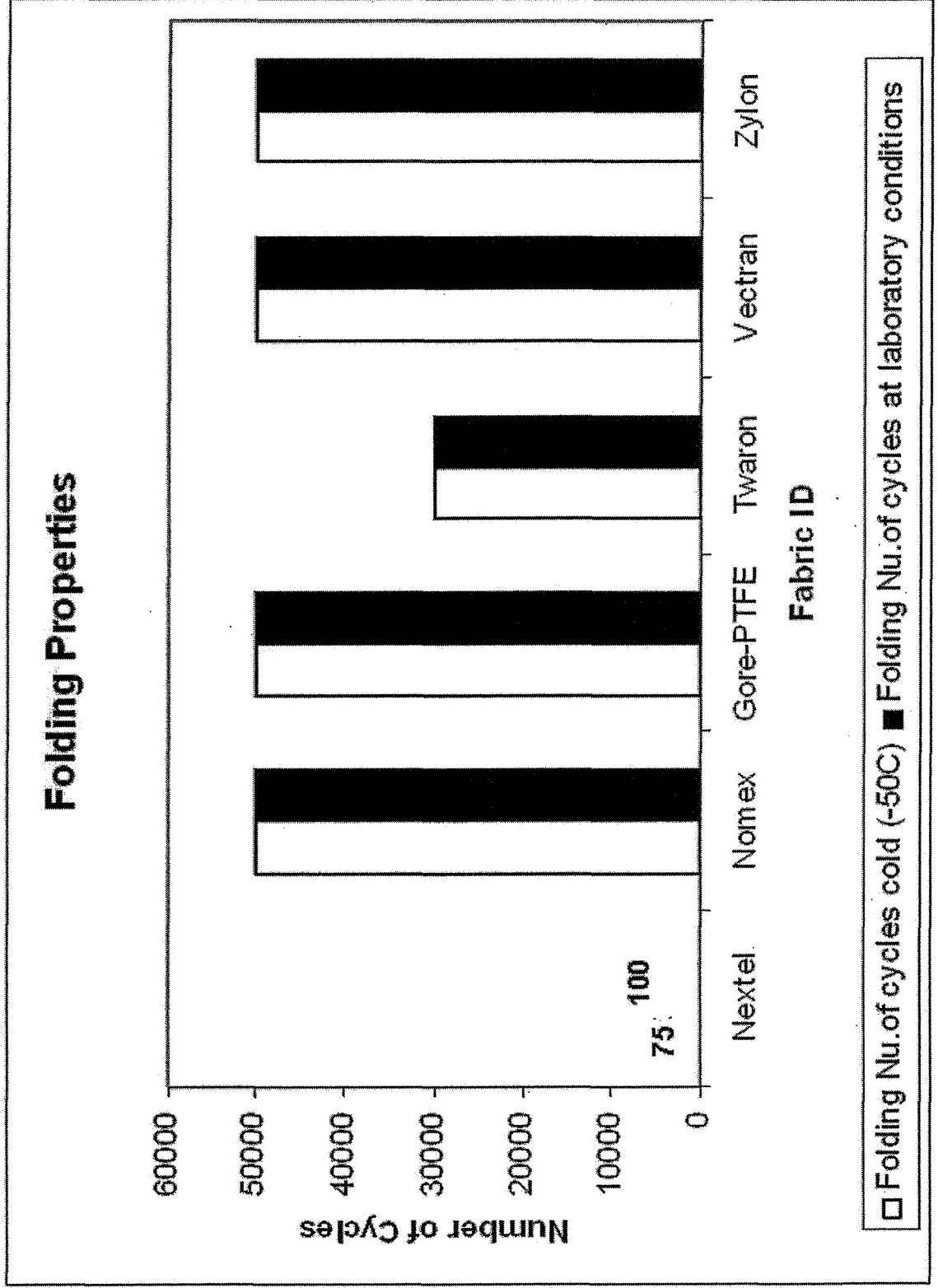
Folding Endurance Results

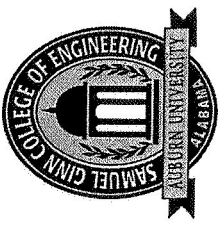


- Nextel TM fabric samples were broken in less than a minute, after 100 cycles on average.
- Twaron TM fabrics started to show damage after 30,000 cycles and were broken at approximately 40,000 cycles.
- For Nomex TM, Gore PTFE TM, Vectran TM, and Zylon TM little damage was seen after 50,000 cycles.



Fold Endurance -- Cold

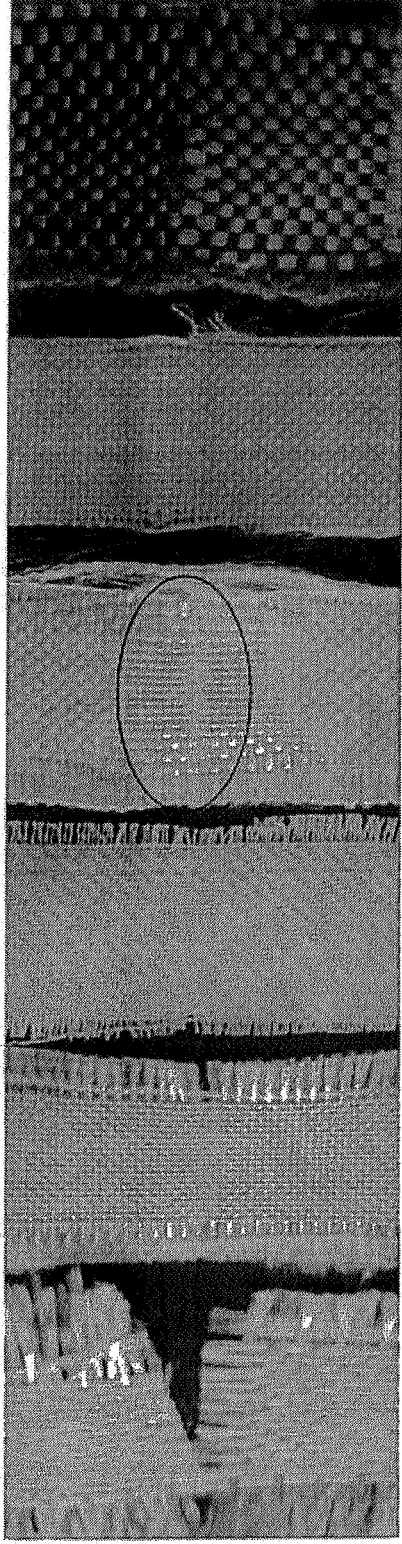




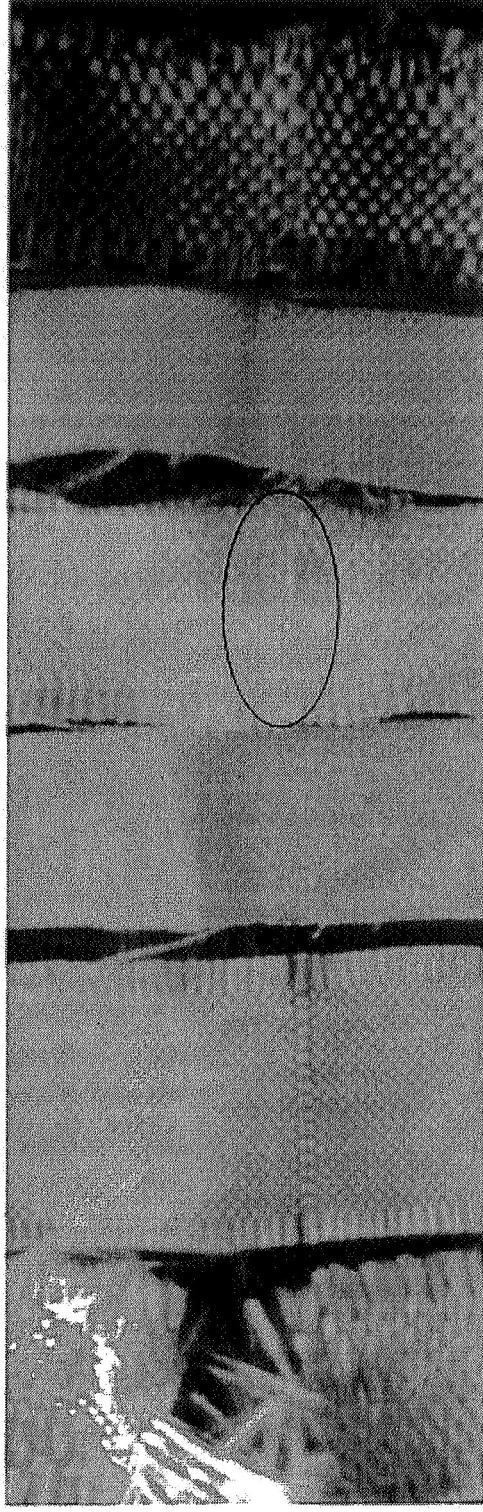
Cryogenic Fold Testing

- The Styrofoam box was used around the fabric folding area.
- Liquid nitrogen was poured over the fabric and the folding mechanism while concurrently running the machine – precise temperature not measured but should approach -195 C.
- The time for testing was restricted to ~one minute - about 100 cycles.
- Fabrics were examined under the microscope. Fold area of all samples and are shown in Figure 2.27.
- Nextel TM fabrics still failed completely after ~ 250 cycles.
- No other fabric showed signs of filament breakage after 100 cycles of folding at cryogenic temperatures.

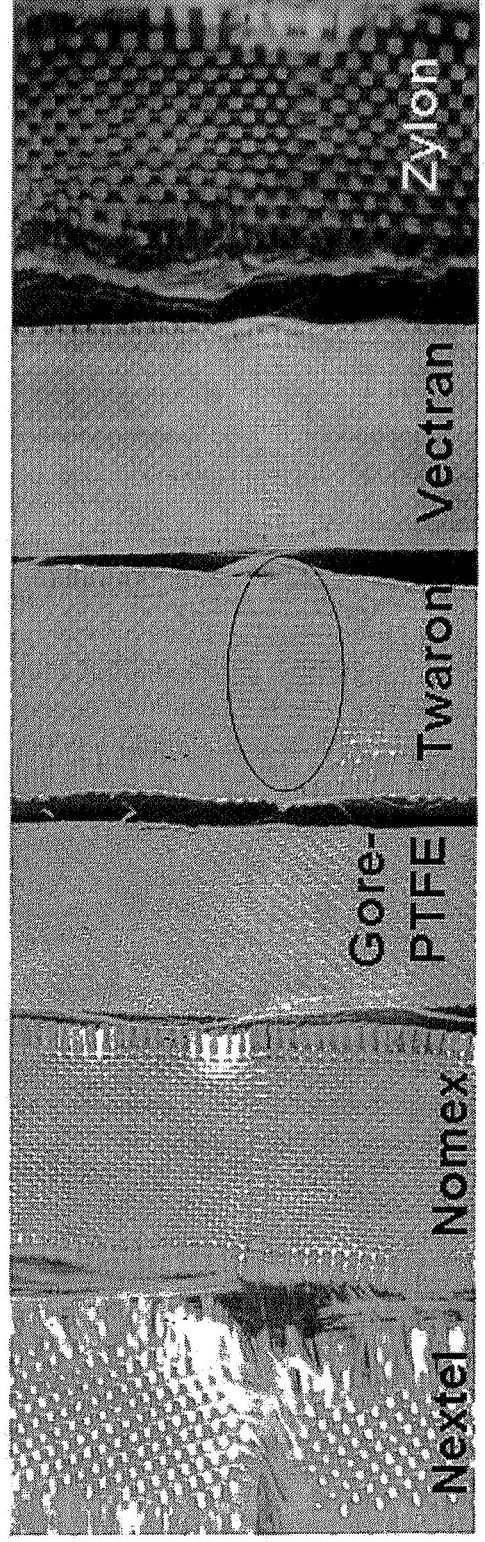
**(a) Ambient
Conditions**

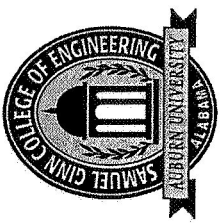


**(b) Cold
Temperature**

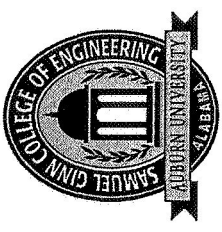


**(c) Cryogenic
Conditions**



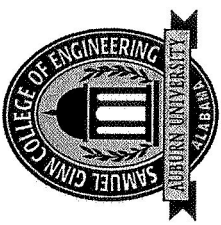


- Folding endurance is unlikely to be a problem for any fabric tested, except Nextel.
- Twaron ranked somewhat poorer in fold resistance than the other organic fibers.



Abrasion Testing

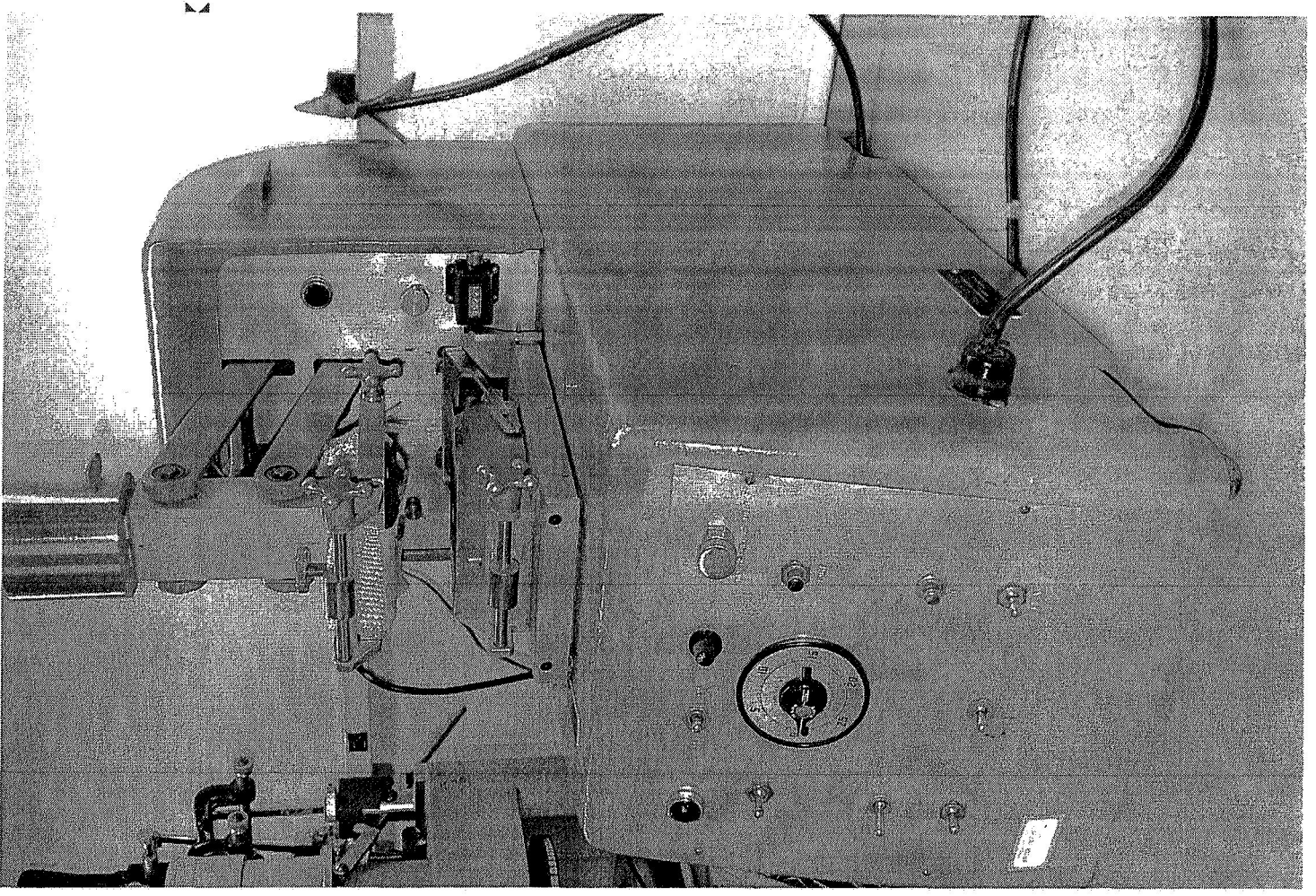
- The resistance of fabrics was determined on a CSI-Stoll Quartermaster Universal Wear Tester (Custom Scientific Instruments Inc.) by a modification of ASTM D-3885 (flexing and abrasion method).
- The resistance to abrasion is affected by many factors: the inherent mechanical properties of the fibers, the dimensions of the fibers, the structure of the yarns, the construction of fabrics and finish type. The resistance of fabrics to abrasion as measured by this method is generally only one of the several factors contributing to durability.

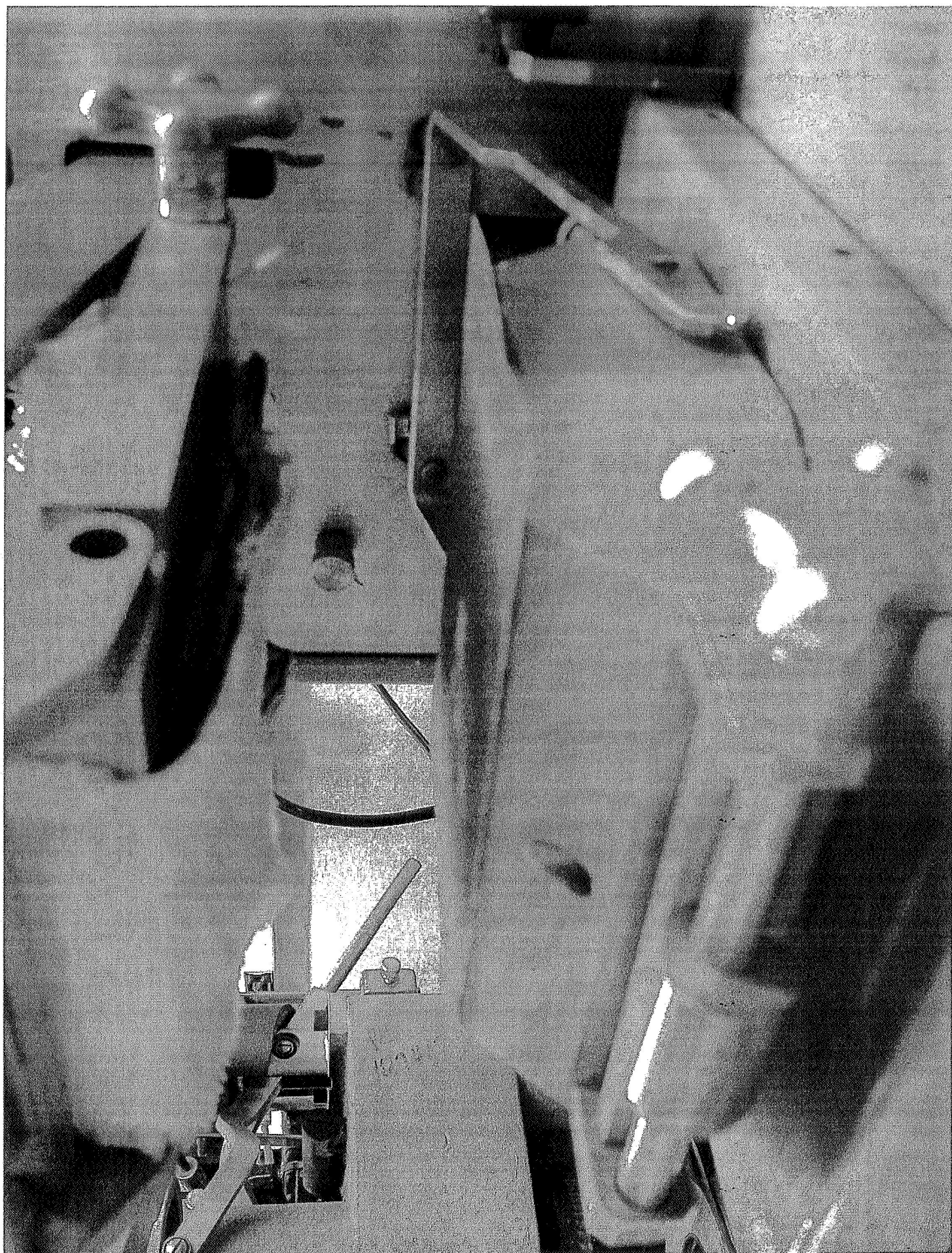


- In this test, 3 fabric samples, cut 3 x 8 inches in both warp and filling direction, are subjected to unidirectional reciprocal rubbing over a sandpaper surface, under 5 pounds weight. The sample is placed between the pressure (upper) plate and reciprocating (lower) plate. The lower plate was covered by sand paper (220 Grit).
- A 2.5mm thick, soft fabric padding was placed under the sample to provide conformability. The number of cycles is recorded upon failure of the fabric or after 1000 cycles.



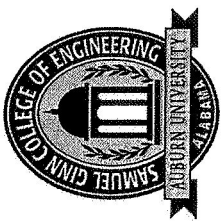
● Stoll Flex-Abrasion Tester



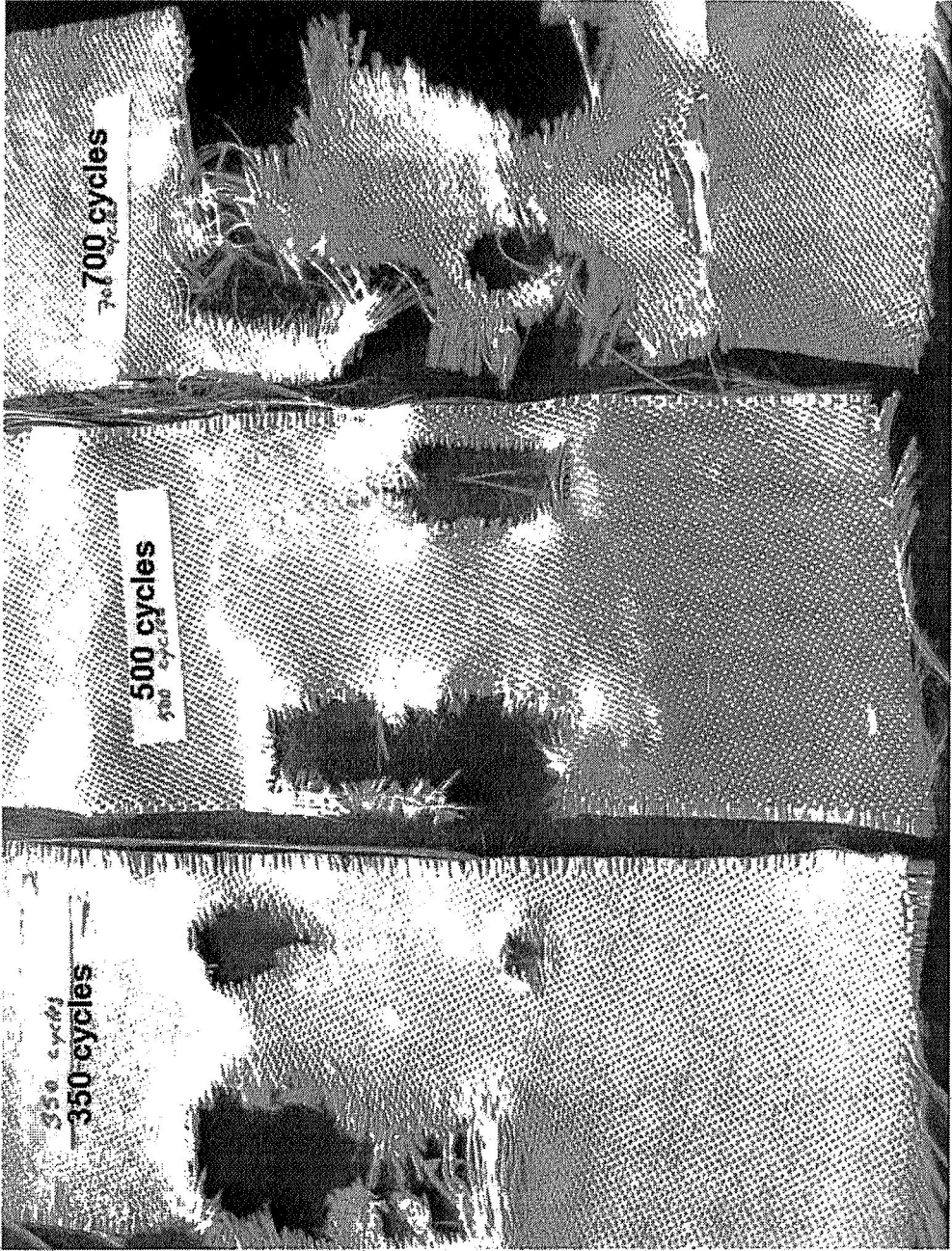
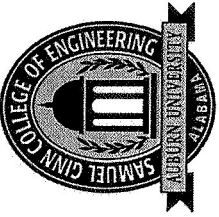




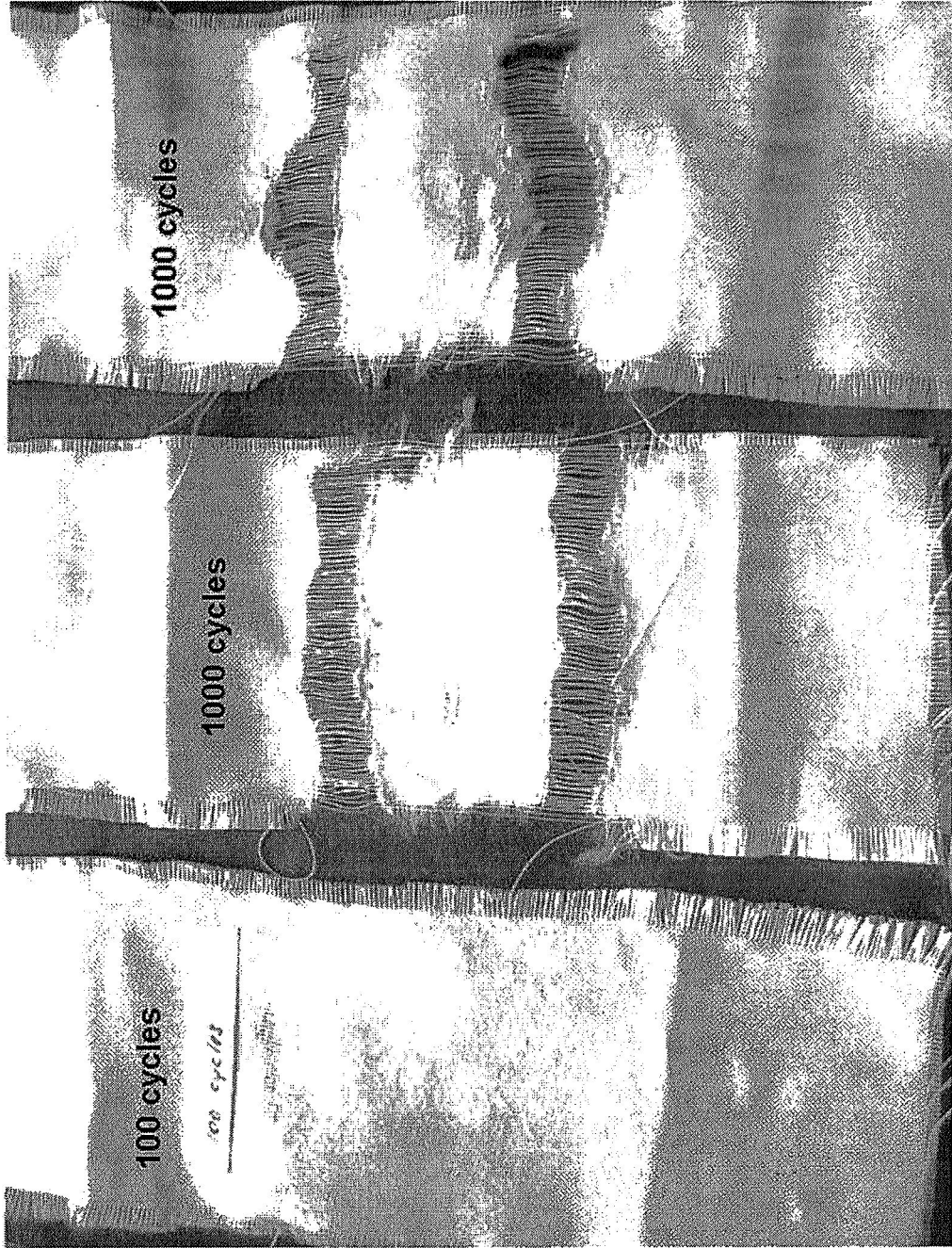
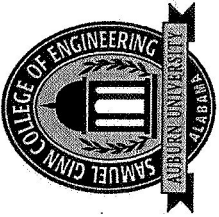
Abrasion Results



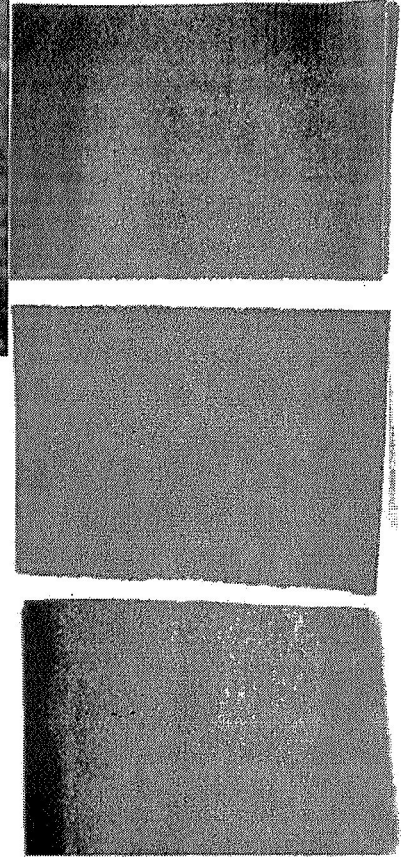
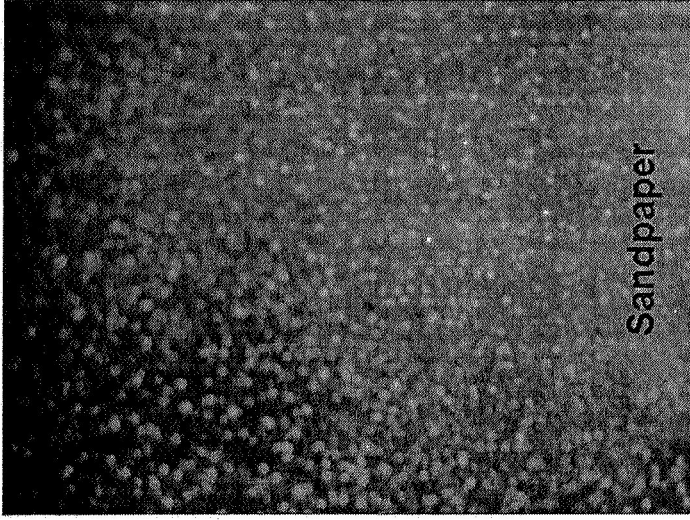
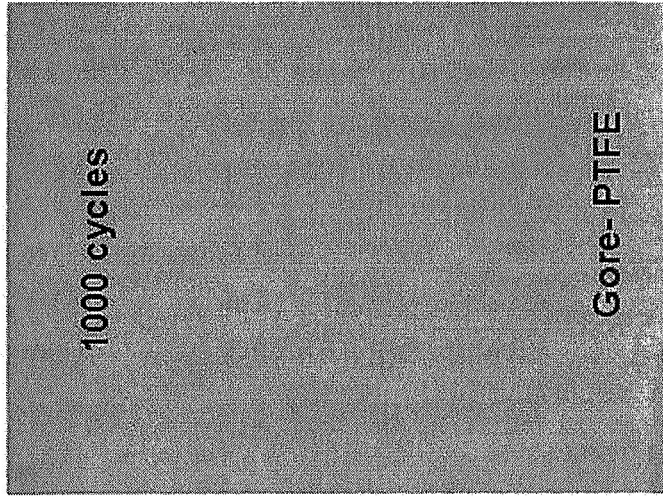
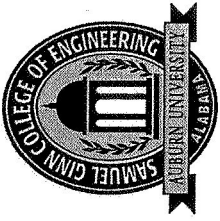
- Gore PTFE TM left some little particles on the sand paper surface but the fabric damage was not excessive.
- Vectran TM and Twaron TM were in very good condition even after 1000 cycles
- Although the failure criteria are somewhat subjective: Nextel TM samples had failed after 350 cycles, and
- Nomex TM and Zylon TM fabrics had failed after 500 cycles



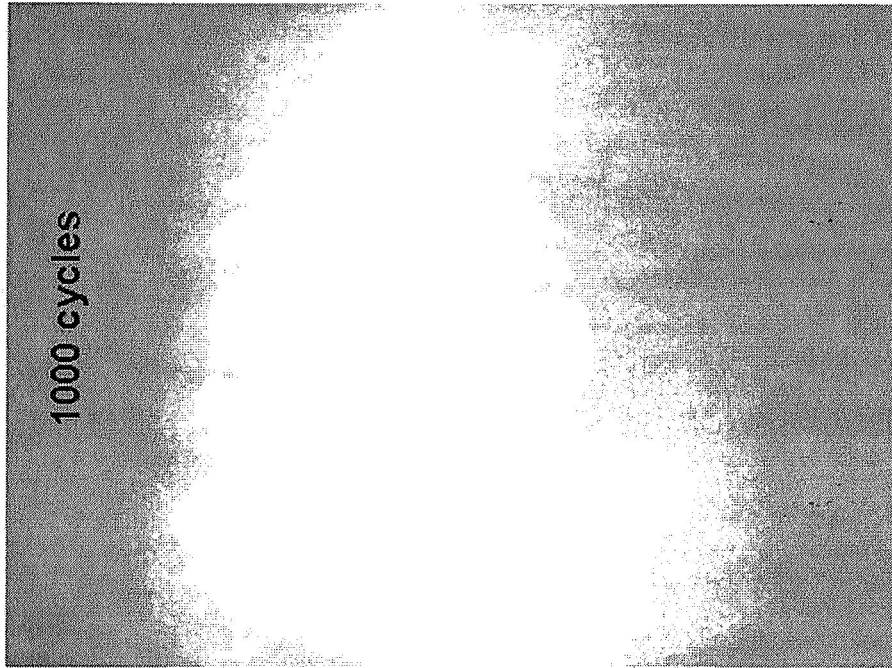
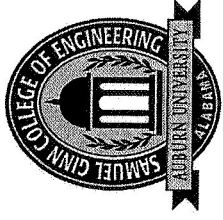
NEXTEL



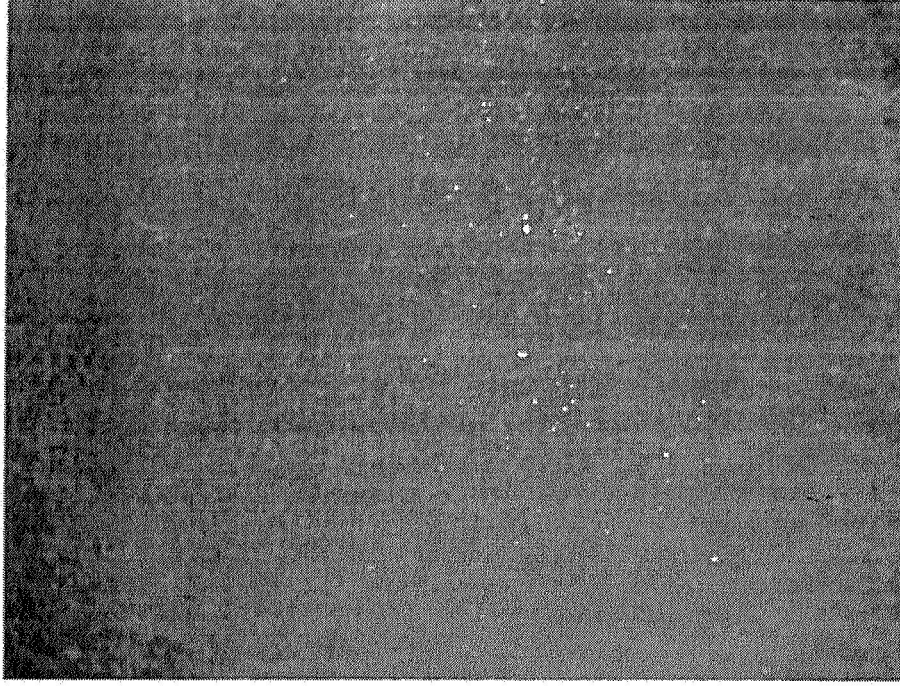
NOMEX



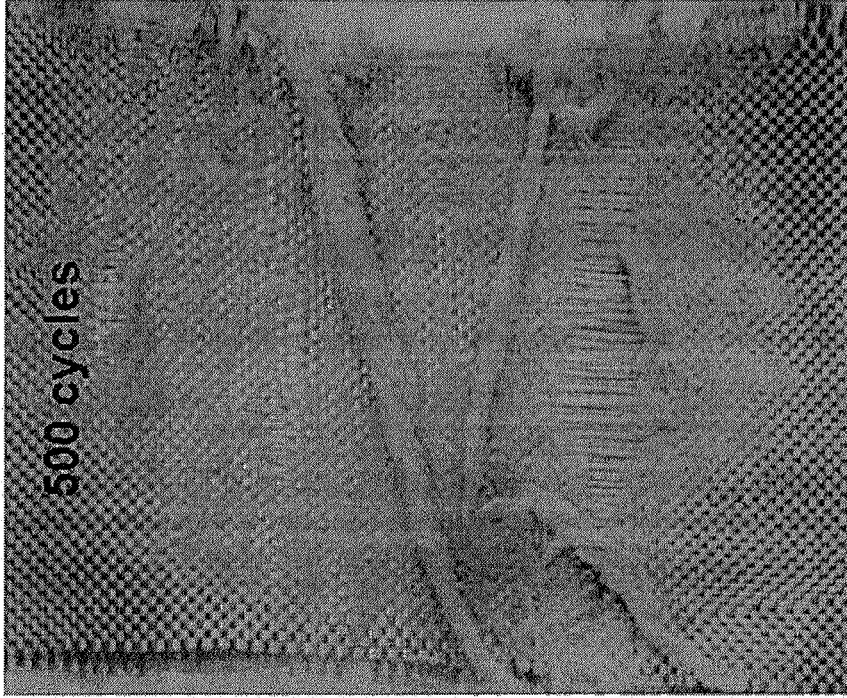
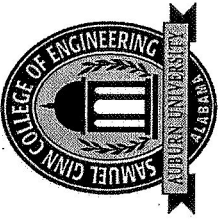
Sandpapers used for abrasion of Gore-PTFE fabrics



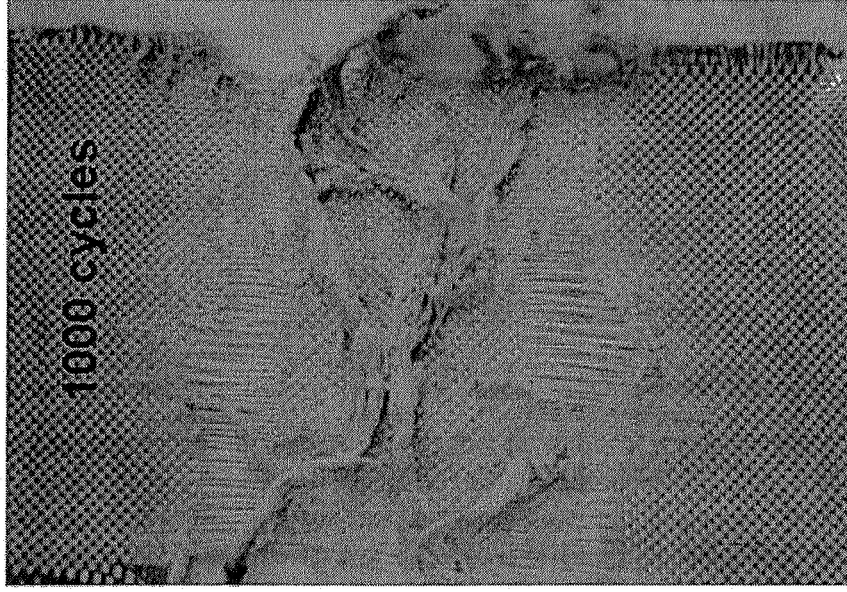
Vectran



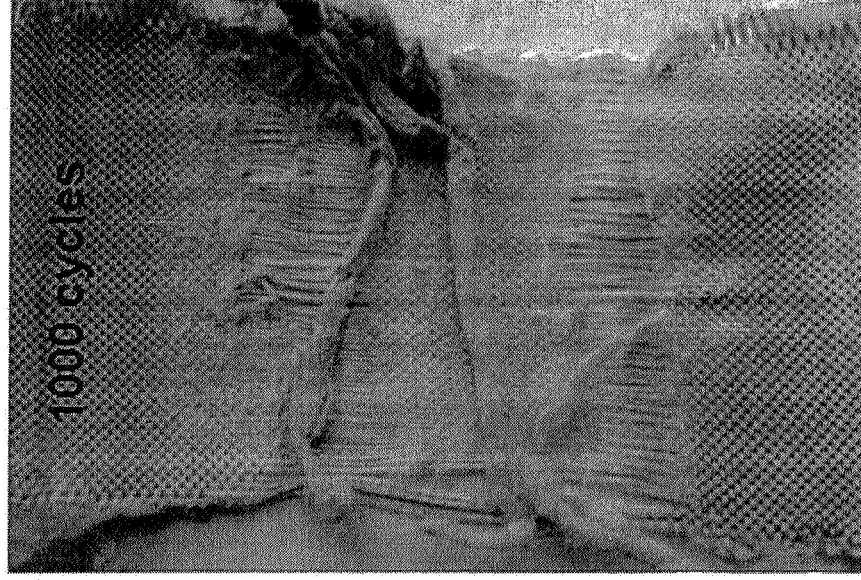
**Sandpaper used for abrasion
of Vectran fabrics**



500 cycles

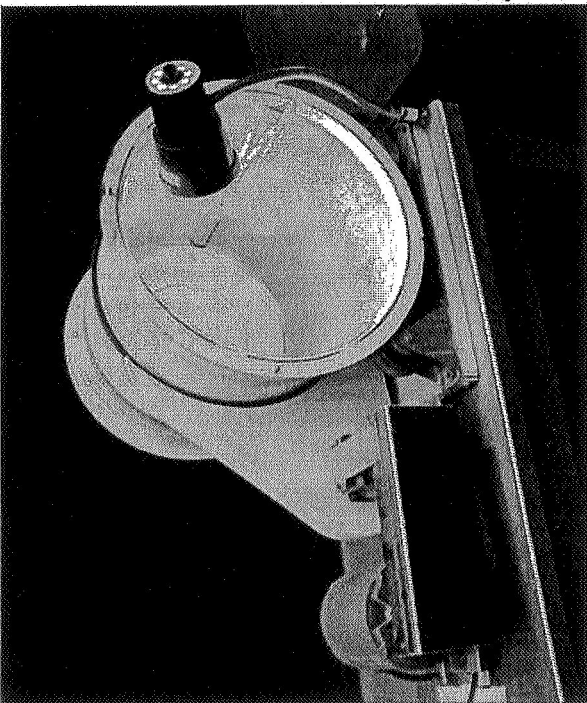
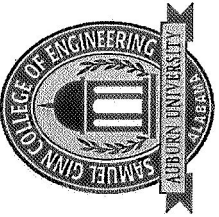


1000 cycles

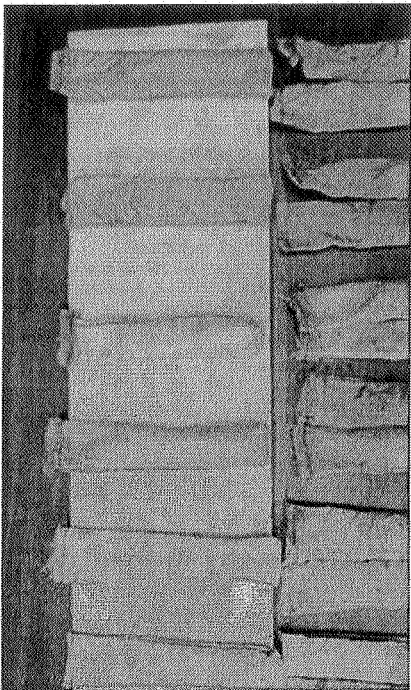


1000 cycles

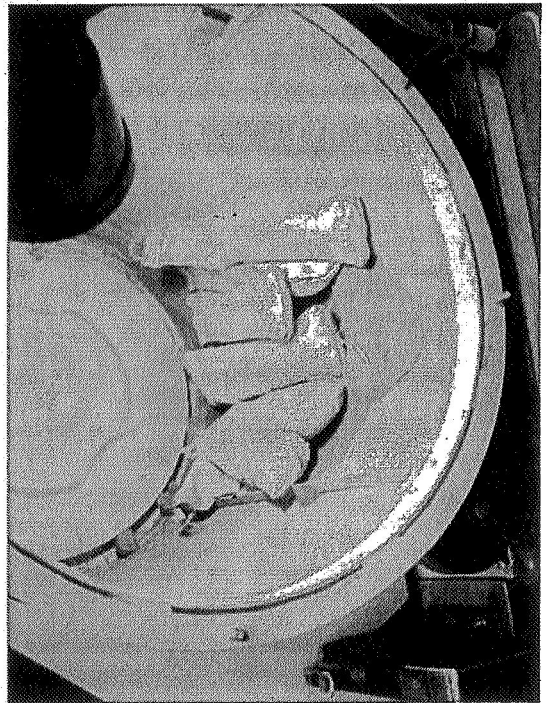
Zylon



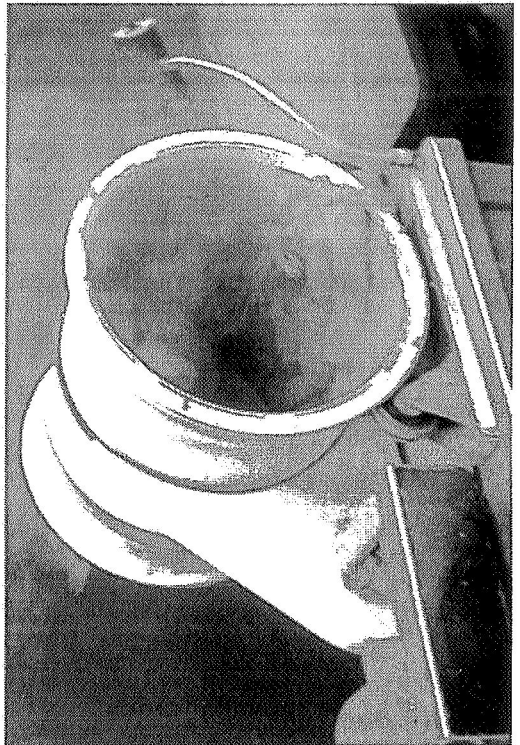
A



B



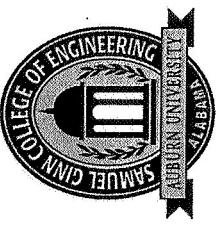
C



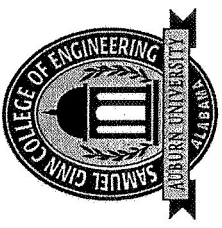
D



JSFC Abrasion Test



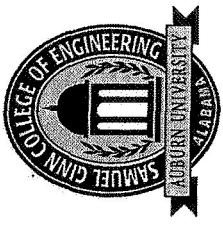
- One bag of each fabric loosely filled bag (of regolith simulant) was placed in the tumbling drum along with regolith simulant on the outside of the bags,
- The drum was rotated at 13rpm for 1 hour.
- Subsequently, the remaining bags were placed in the drum and were tumbled for 1 hour.



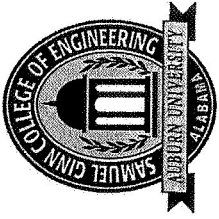
- The fabrics were examined for damage by carefully ripping out the seams and gently shaking the fabrics in a pail of water to dislodge the regolith simulant.



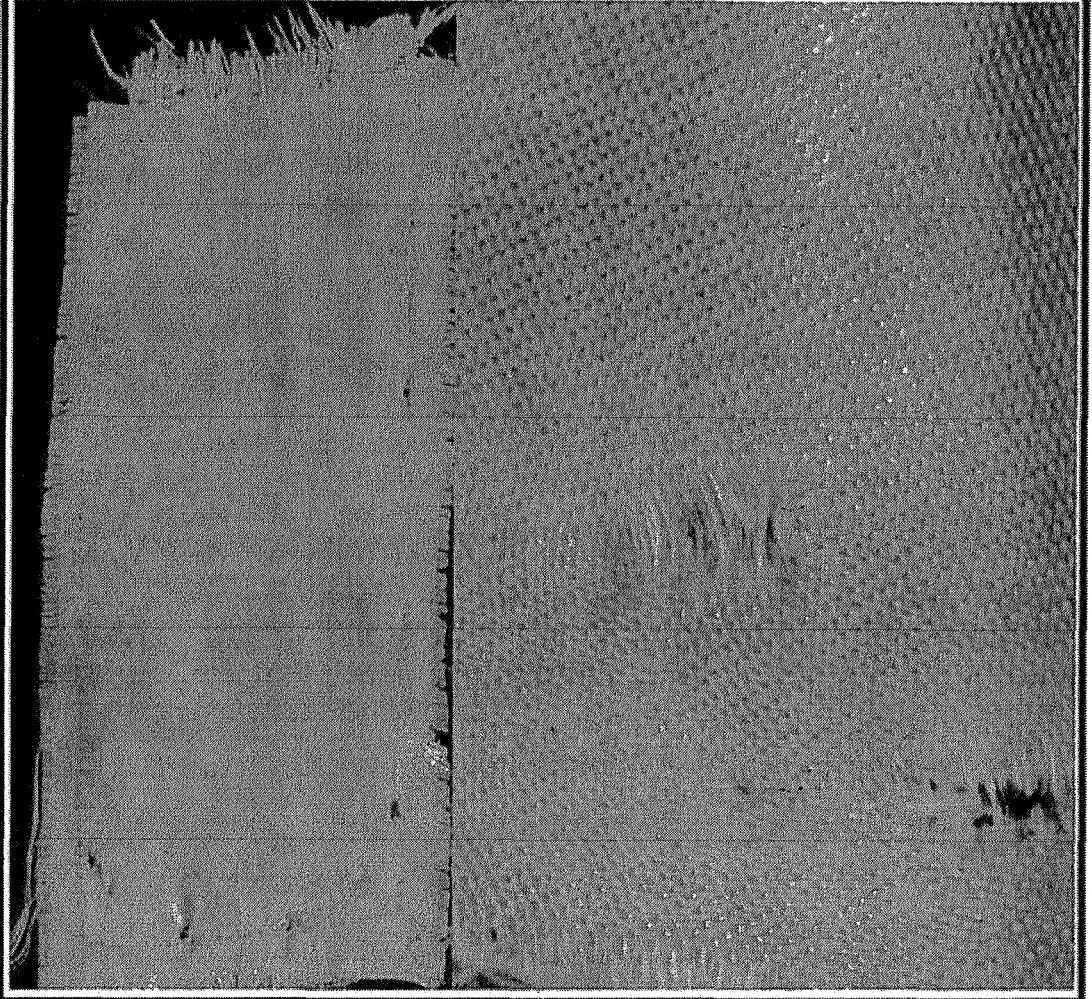
JSFC Abrasion Results

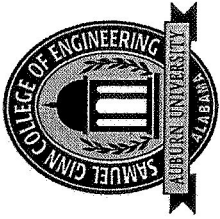


- Nextel and Gore PTFE showed some damage, but mainly at the seams.
- The other fabrics were essentially undamaged.

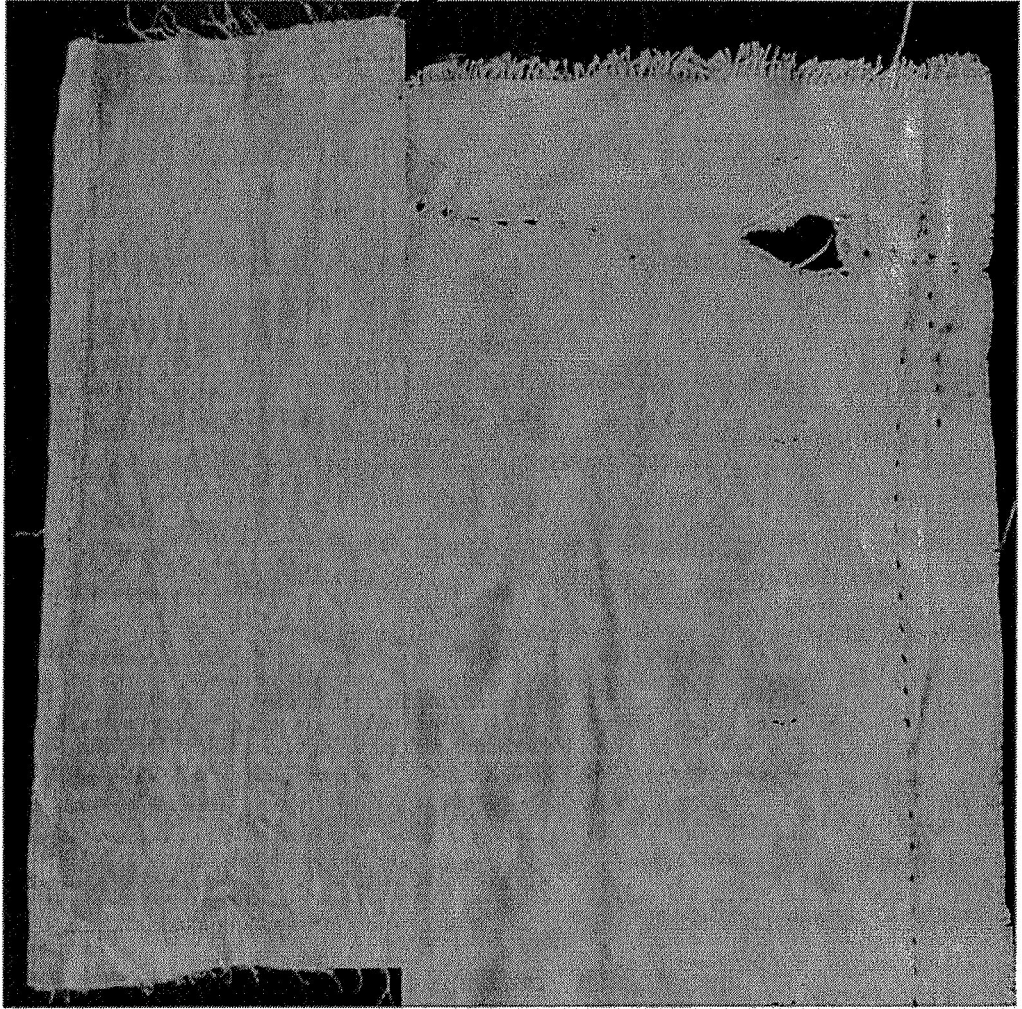


Nextel™



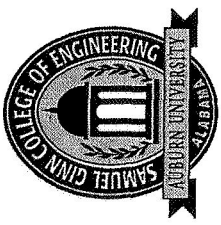


Gore-PTFE™





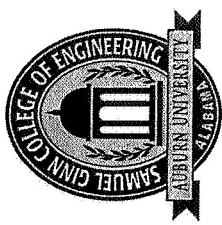
MSFC Testing



- Mary Nehls, Dr. Steve Evans, Mary Hovater
EM50; Dr. Scott Miller/Qualis/ SEE Testing at
MSFC (Part I)
- Mary Nehls and Her Team, SEE Testing at
MSFC (Part II)



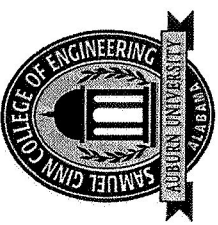
Radiation Resistance



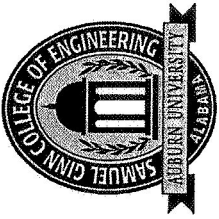
- Vacuum Ultra Violet - VUV
- Particle radiation
- Gamma radiation
- Compare strength before and after radiation.
- VUV and particle radiation had limited samples
- VUV tested only Nextel, Gore PTFE and Vectran



VUV Radiation Resistance

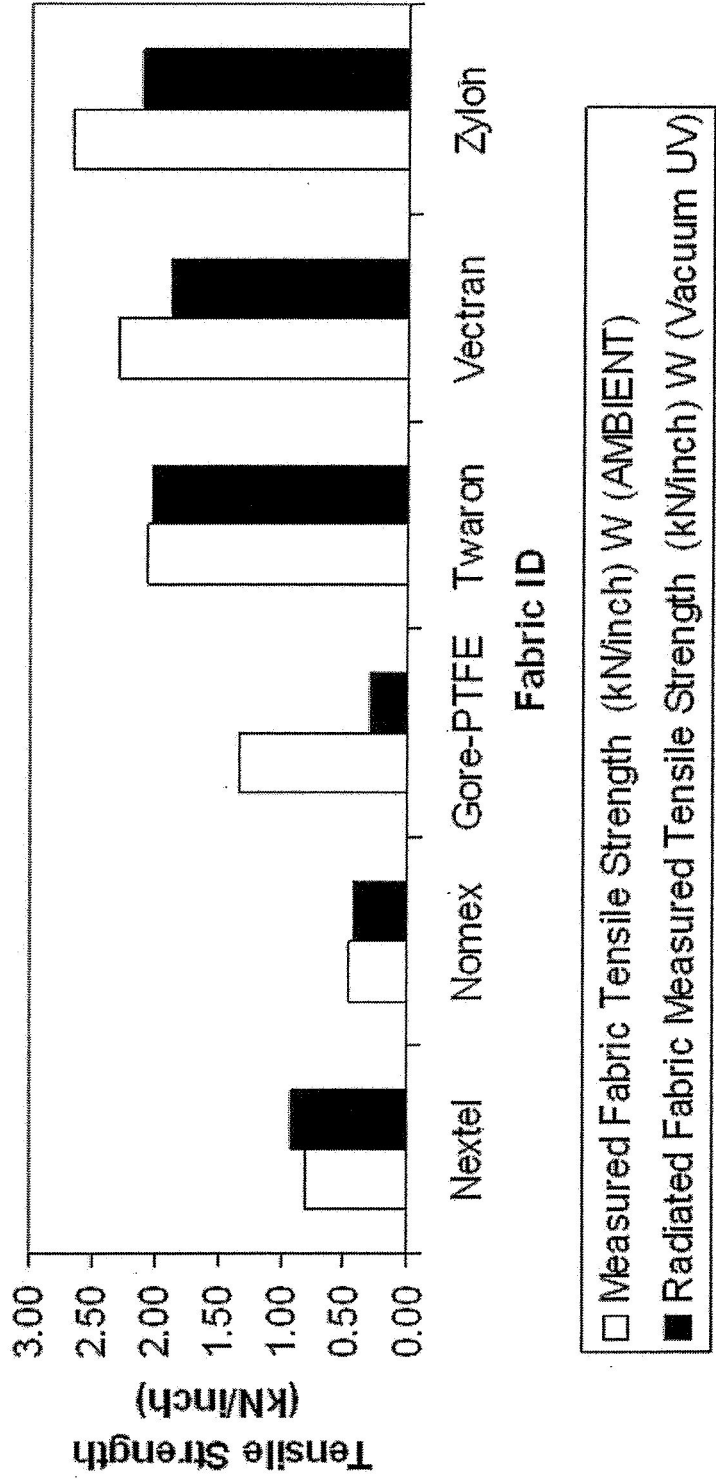


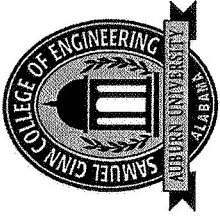
- Limited samples all six fabrics but only warp direction.
- Only 3 samples per fabric:



VUV Radiation Results

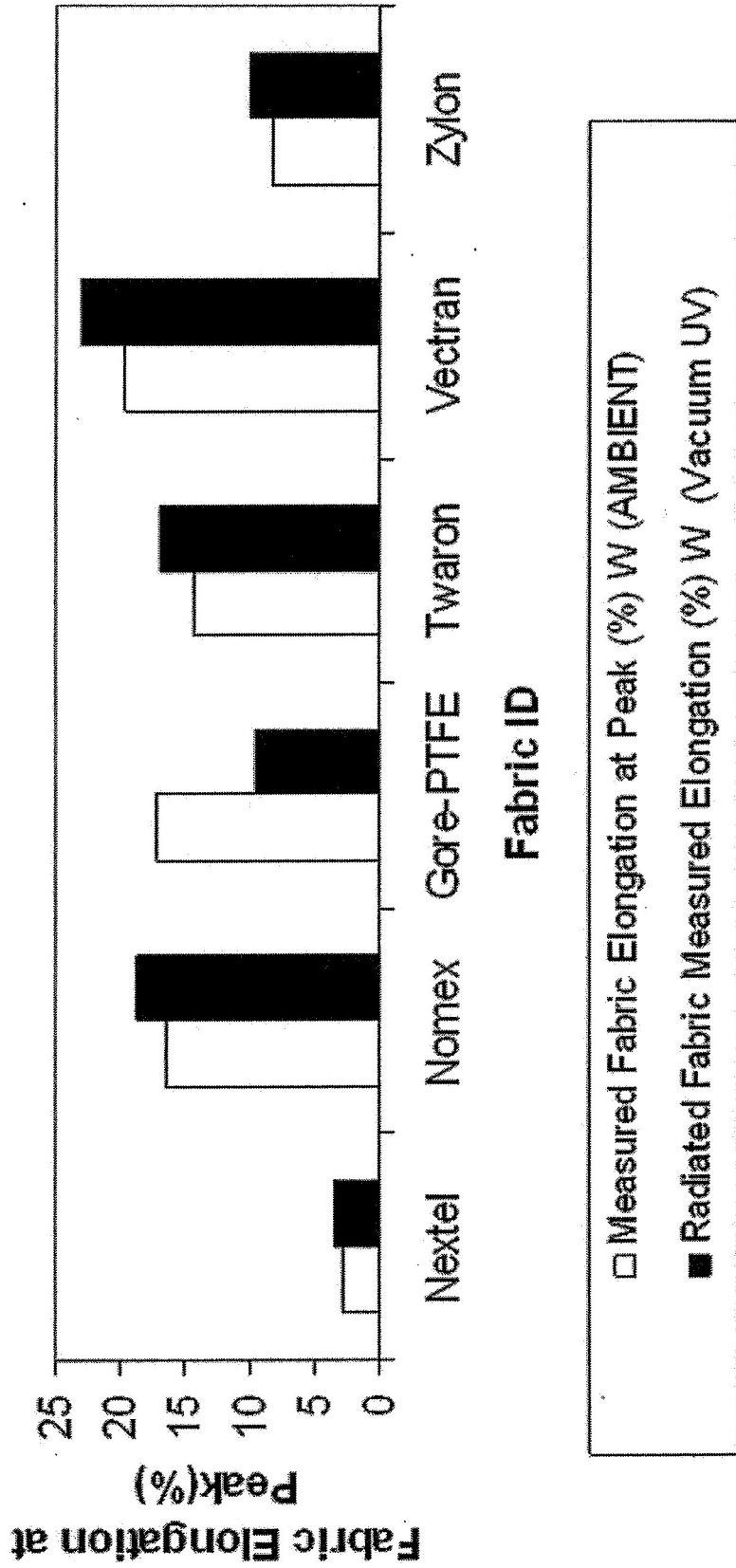
Comparison of Fabric Tensile Strength (kN/in) Before and After Radiation (Vacuum UV) (Warp Direction)





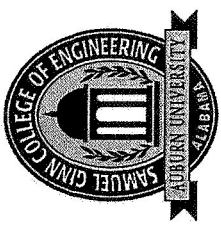
VUV Radiation Results

Comparison of Fabric Elongation (%) Before and After Radiation
(Vacuum UV) (Warp Direction)

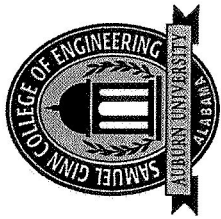




Particle Radiation Resistance

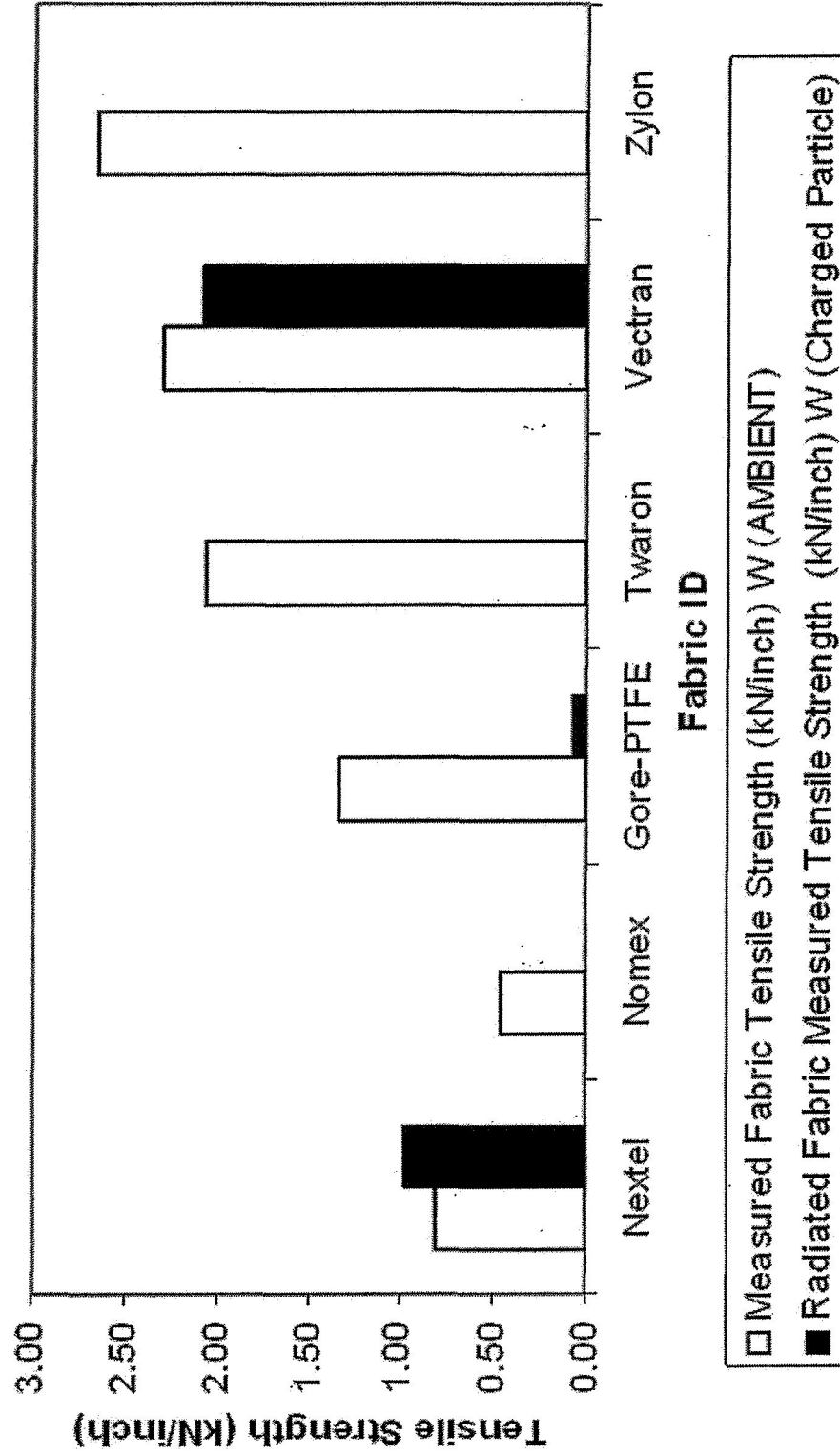


- Limited exposure area
- Only three fabric samples exposed:
 - Nextel
 - Gore PTFE
 - Vectran



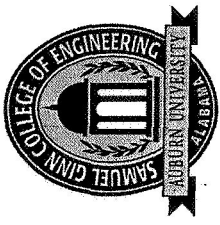
Particle Radiation Results

Comparison of Fabric Tensile Strength Before and After
Radiation (Charged Particle) (Warp Direction)

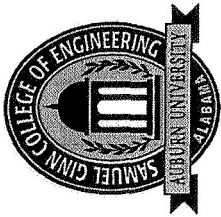




Gamma Radiation Results

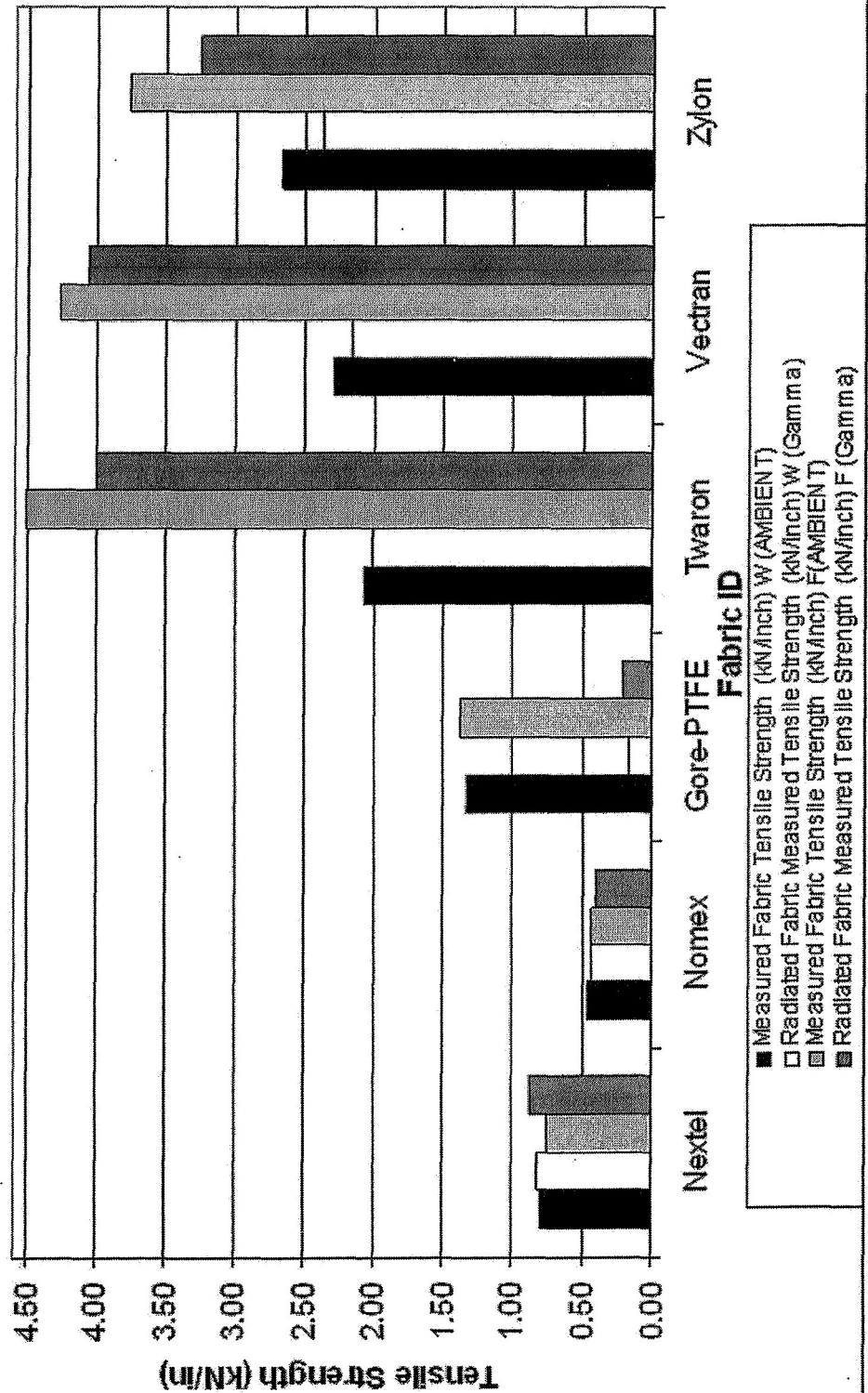


- Exposure to 10 megarads over one day.
- Co ⁶⁰ radiation source at Auburn University
- Under vacuum and dry

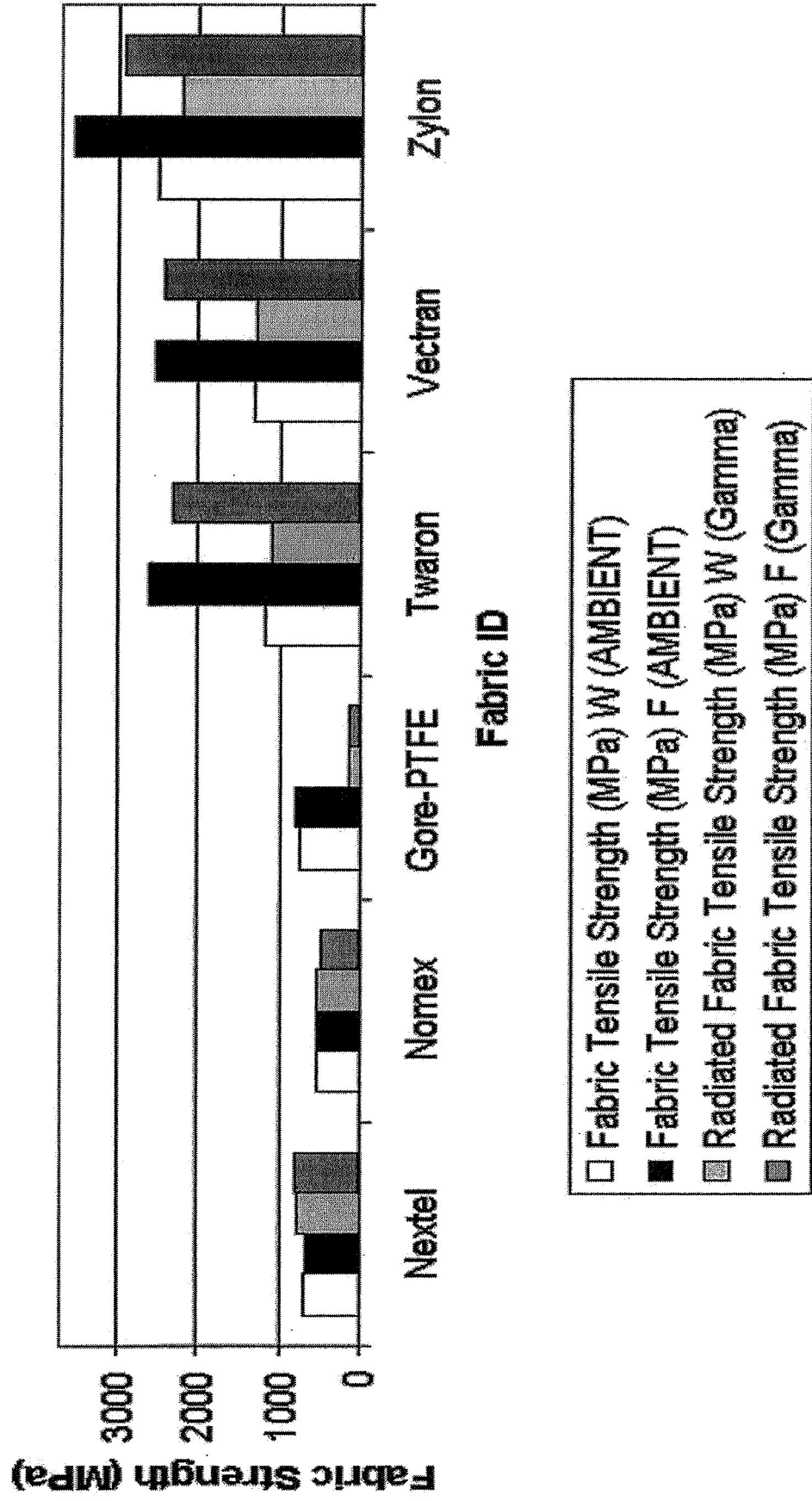


Gamma Radiation Results

Comparison of Fabric Tensile Strength (kN/in) Before and After Radiation (Gamma)

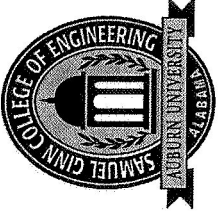


**Comparison of Fabric Tensile Strength (MPa) Before and After Radiation
(Gamma)**

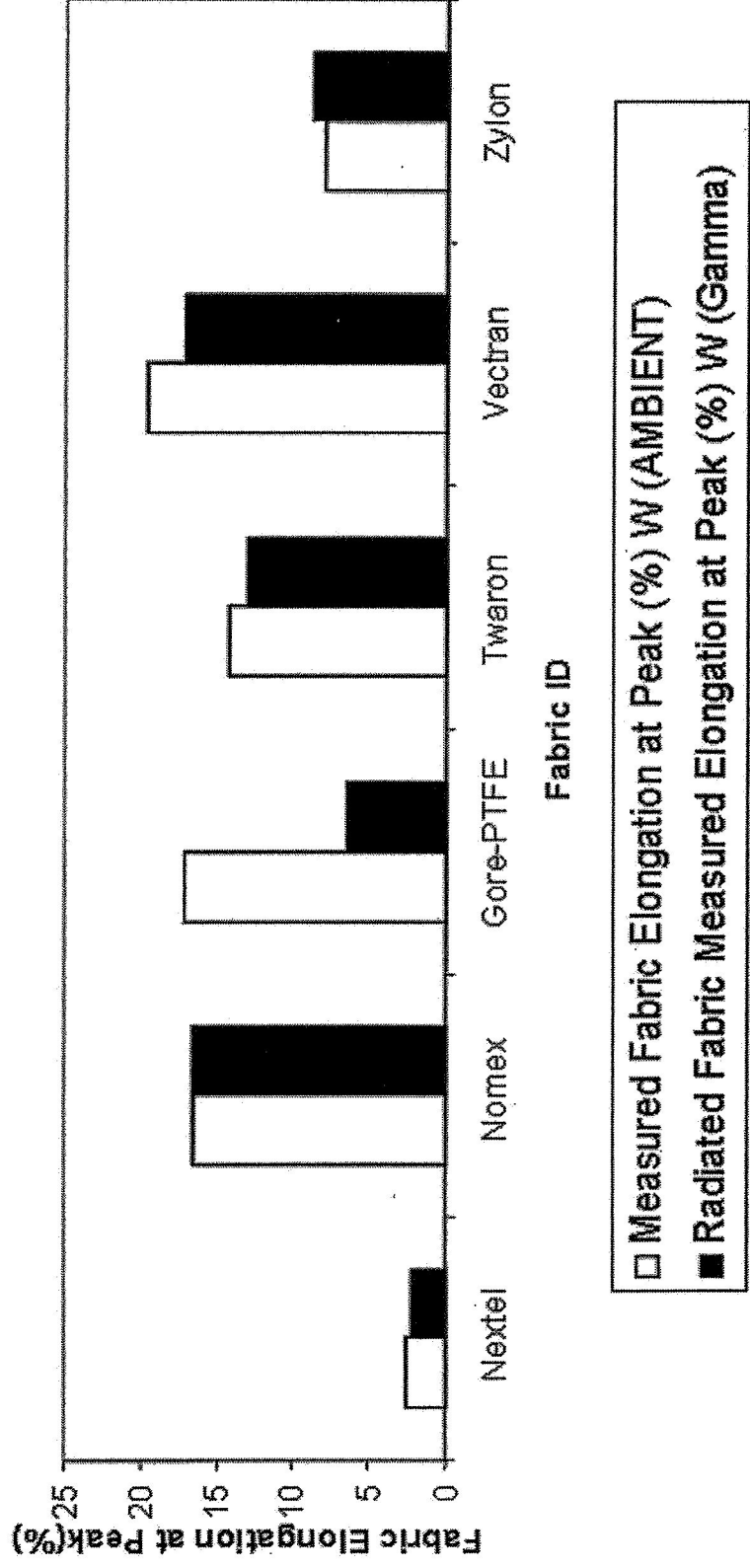




Gamma Radiation Results

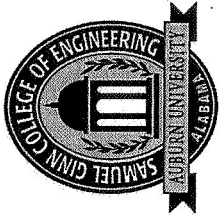


Comparison of Fabric Elongation (%) Before and After Radiation
(Gamma) (Warp Direction)

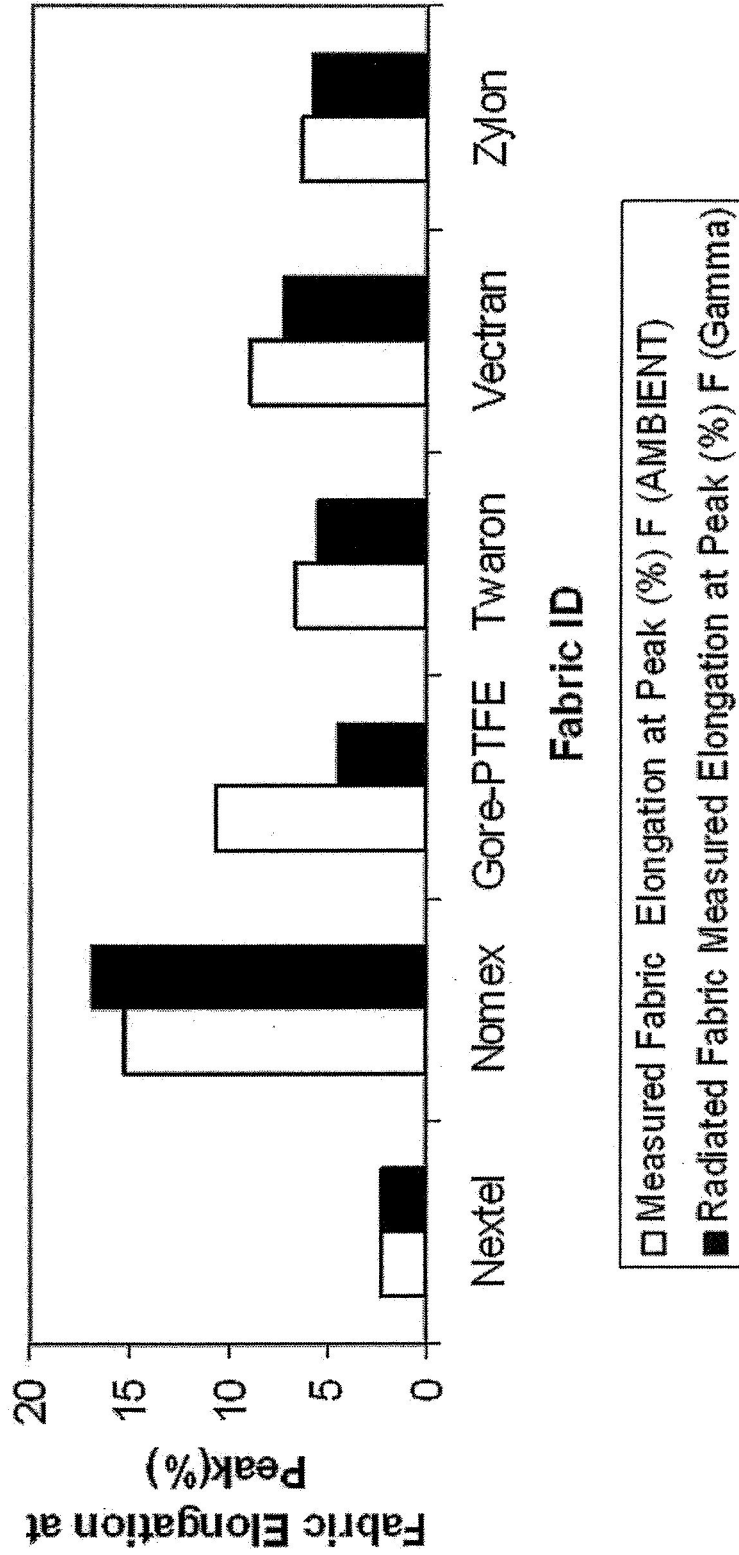




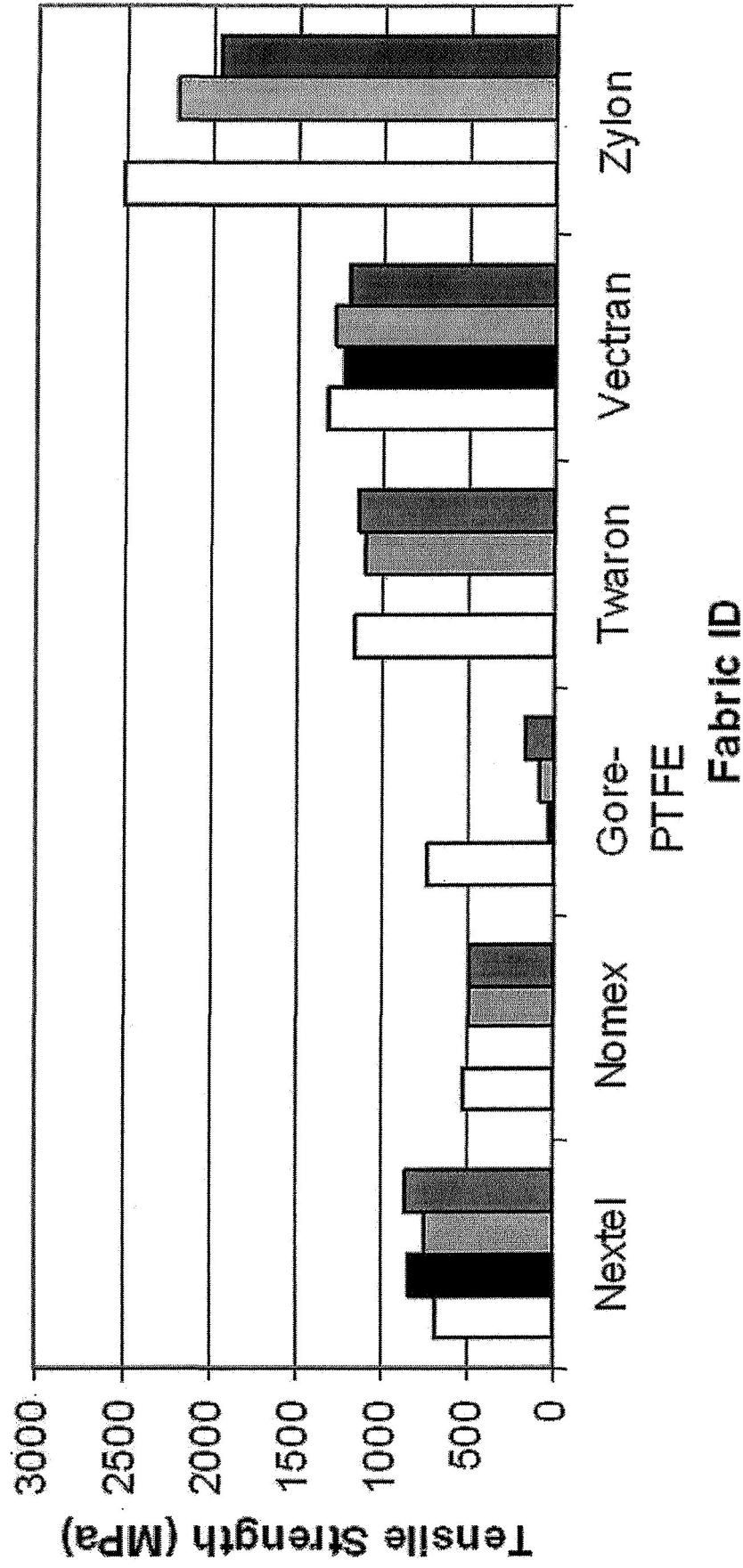
Gamma Radiation Results



Comparison of Fabric Elongation (%) Before and After Radiation
(Gamma) (Filling Direction)

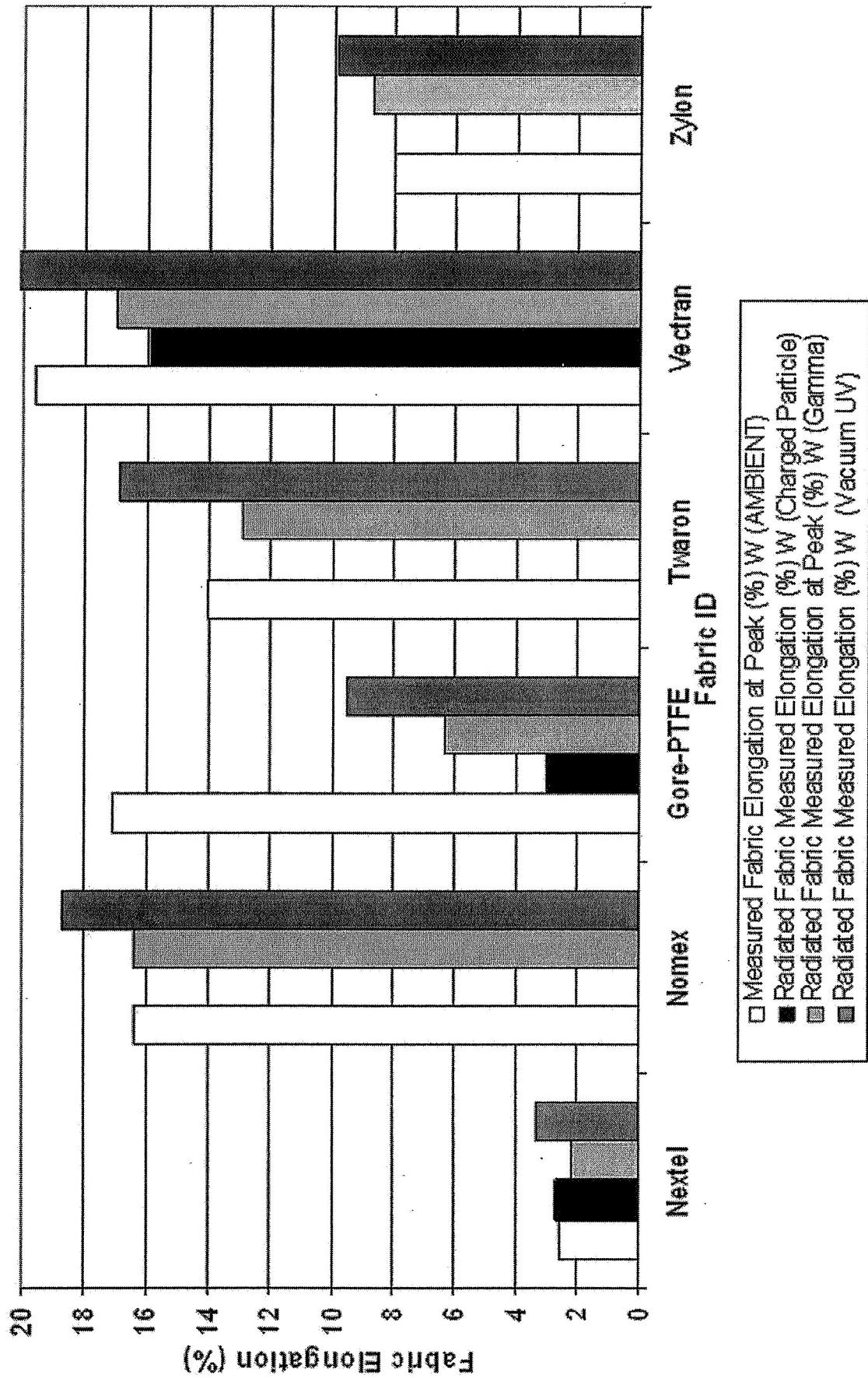


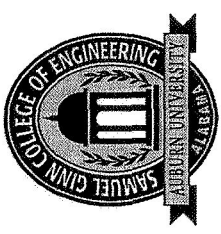
Comparison of Fabric Tensile Strength (MPa) Before and After Radiations (Warp Direction)



- Fabric Tensile Strength (MPa) W (AMBIENT)
- Radiated Fabric Measured Tensile Strength (MPa) W (Charged Particle)
- ▒ Radiated Fabric Tensile Strength (MPa) W (Gamma)
- Radiated Fabric Tensile Strength (MPa) W (Vacuum UV)

Comparison of Fabric Elongation (%) Before and After Radiations





Design Specification

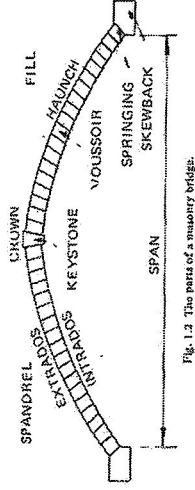
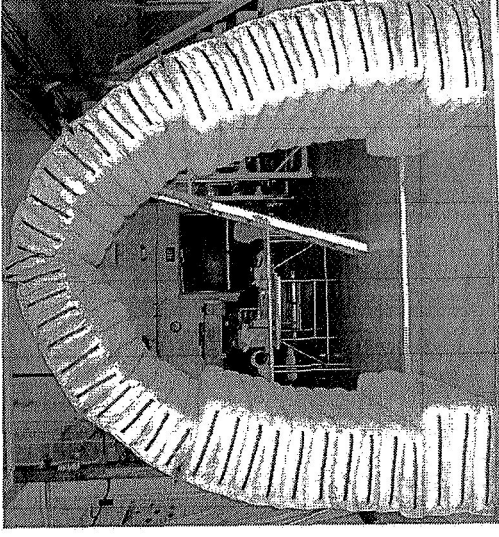


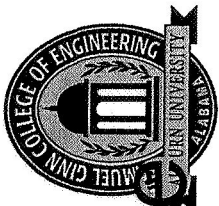
Fig. 1.2 The parts of a masonry bridge.



Fig. 1.3 Voussoirs and passers at Tentoyudd (photographed by Ter Ruldsloot, reproduced by permission of Cambridge University Press).

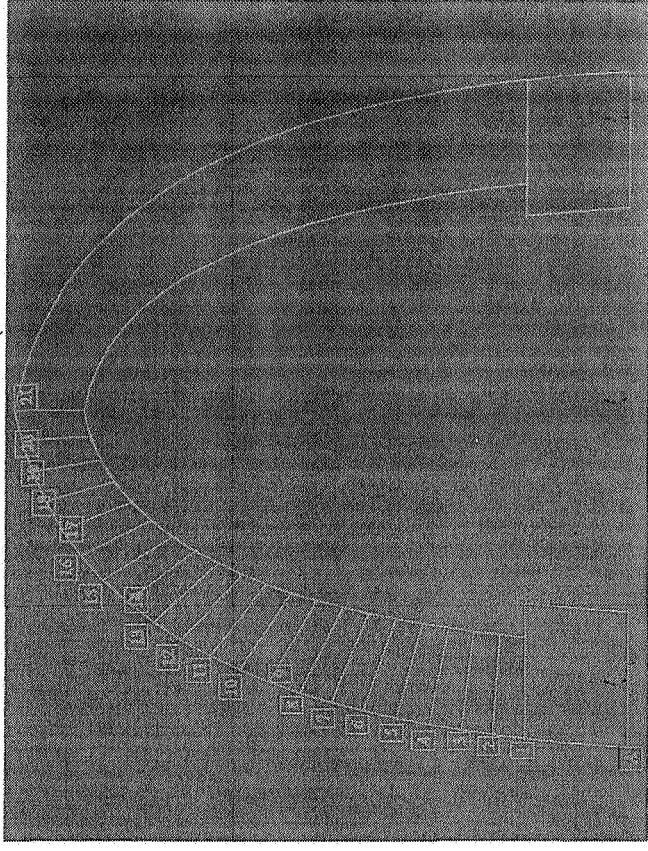


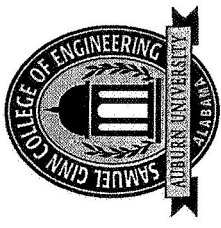
- From Gweneth Smithers: A regolith bag (preferably self-supporting) arch structure at least 6' high, 6' wide and 6' deep.
- To be erected at MSFC.



Final Design – Construction Template

- The fabric consisted of a top Kevlar layer, to which fabric “teeth” were stitched. “Top Connected Bag Configuration”
- Construction Template – x-y coordinate of numbered points
- Template based on structural analysis techniques for masonry arches (“Funicular Polygon”).
- A catenary shape
- Pipes attached to frame were used as guides at points 10, 14 and 21.



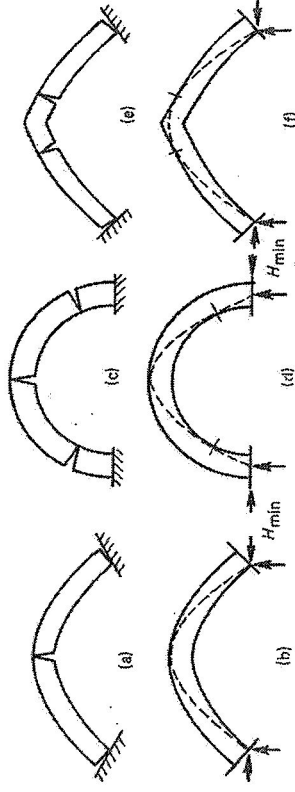
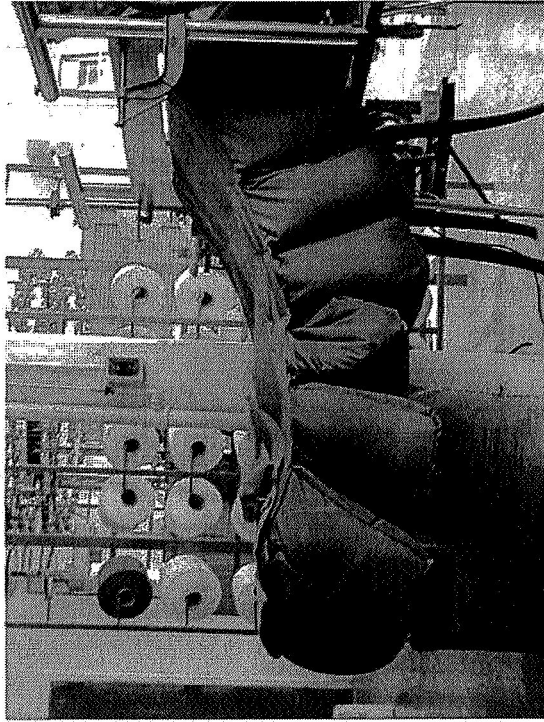
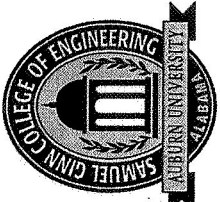


Concepts That Led to the Design

- Vermiculite was chosen to simulate regolith; Its weight on earth/unit volume (density .16-.2 g/cc) is the nearest that of weight of lunar regolith/unit volume (density .27 g/cc) of any bulk material.
- Strength of vermiculite-filled bags depends on vermiculite pressure. At high pressure, the grain interlock, increasing resistance to shearing failure of the vermiculite. Pressure could be generated by
 - 1) Weight and loads from the structure above. Used for bottom bags.
 - 2) Packing the bags tightly so they strain the bag, and try to round. Used for top bags.
- The "beam" (next slide) demonstrated the advantages of the "top-connected" configuration for erecting of the structure, by being able to support bending loads.
- The assumptions used to design a masonry arch were assumed valid for the design the regolith bag arch. These include: 1) No sliding between bags, 2) Only compressive forces are transmitted across brick boundaries (bricks cannot transmit tensile loads), 3) The bricks have infinite compressive strength.
- Masonry Arches fail by "hinging". This was also observed in the regolith bag arch.
- The foundation provides the horizontal force at the base. Taller arches are more stable. Build the arch on a frame, then remove the frame.

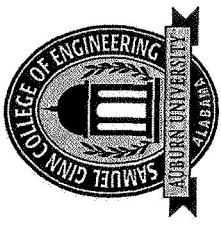


Useful Concepts That Led to the Design

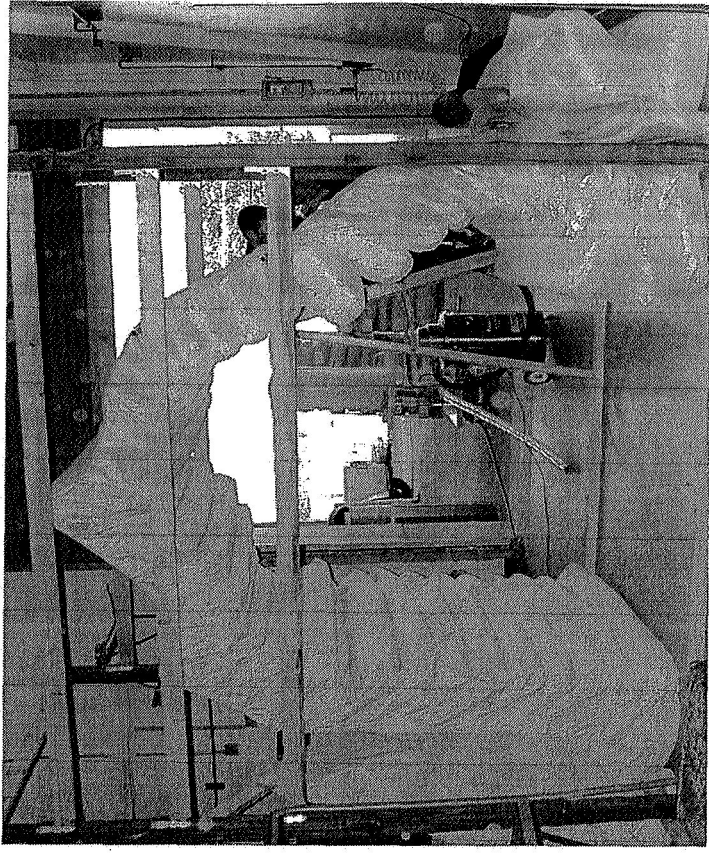




The Final Garage Structure – A Top-Connected Regolith Bag Arch

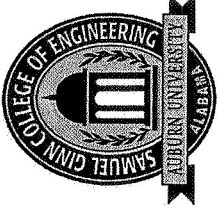


- Notice top fabric layer and bags (“teeth”).
- Fabric made from coated Kevlar
- Zippers (other side) for filling
- Wooden frame with pipe supports at locations dictated by the construction template
- Used 46 of 60 bags

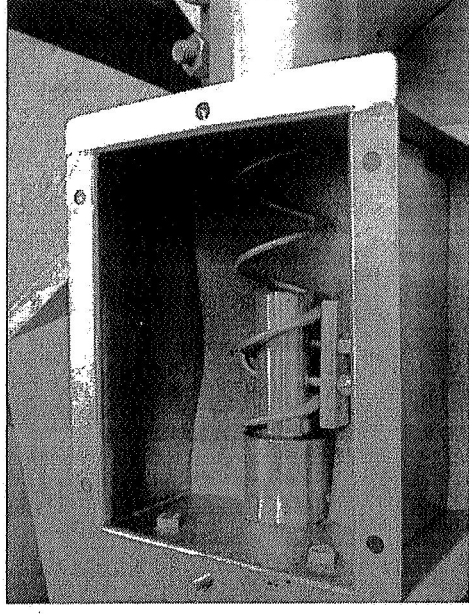
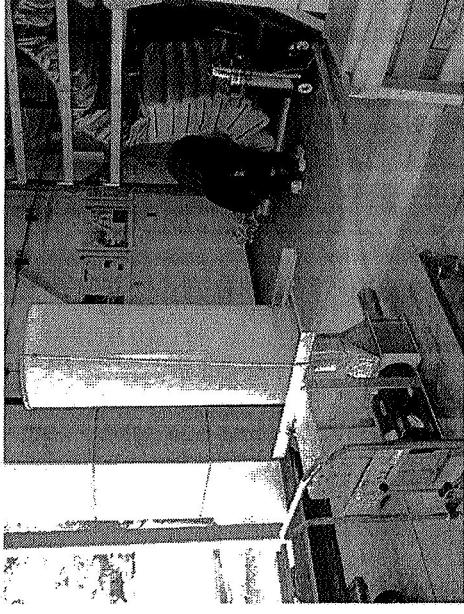




How Bags Were Filled

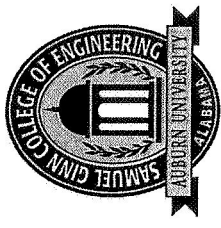


- Series 300 Haupman helical flexible screw conveyor system, with green hopper.
- 3" diameter, 12' helical screw inside pipe had no central shaft, making screw axially flexible, limiting the feed force. This significantly impacted the ability to fill bags with substantial pressure.
- The pipe was inserted to the end of the bag and slowly withdrawn as vermiculite filled the bag.





Packing of Lower Bags

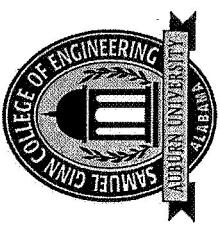


- Bottom bags (2'x6"x6") were filled and patted down flat and worked to about 6"-8" thickness. They were not allowed to "round" substantially
- Strength of these bags came from weight of vermiculite above

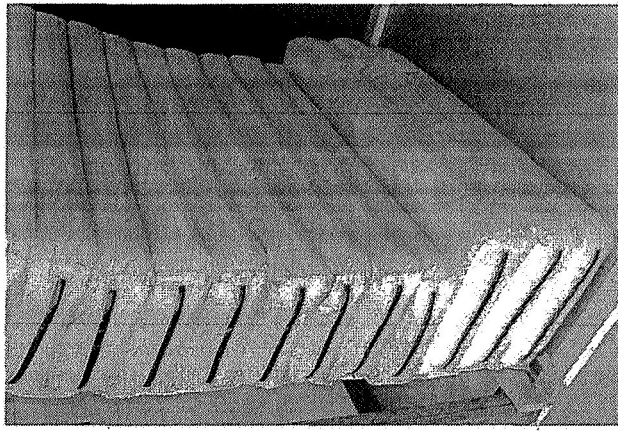


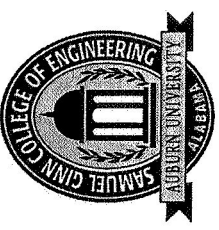


Building Upward



- Notice zippers
- Bag were filled, and bags positioned along a path of the outside fabric meant to reach the guide points.
- Both sides were built upward together.





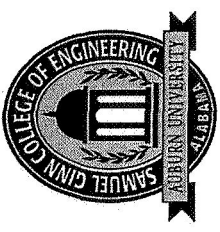
Filling Bags at the Top

- Bags were packed tighter as construction moved toward the top, causing them to round.
- At the very top, it was difficult to fully pack the bags with the screw conveyor because of its limitations on force. With a more forceful screw, a true “keystone” would have been achievable.
- The space for the top 3 or 4 bags before filling was confined by neighboring bags.
- Pipes were removed and structure remained standing after settling.

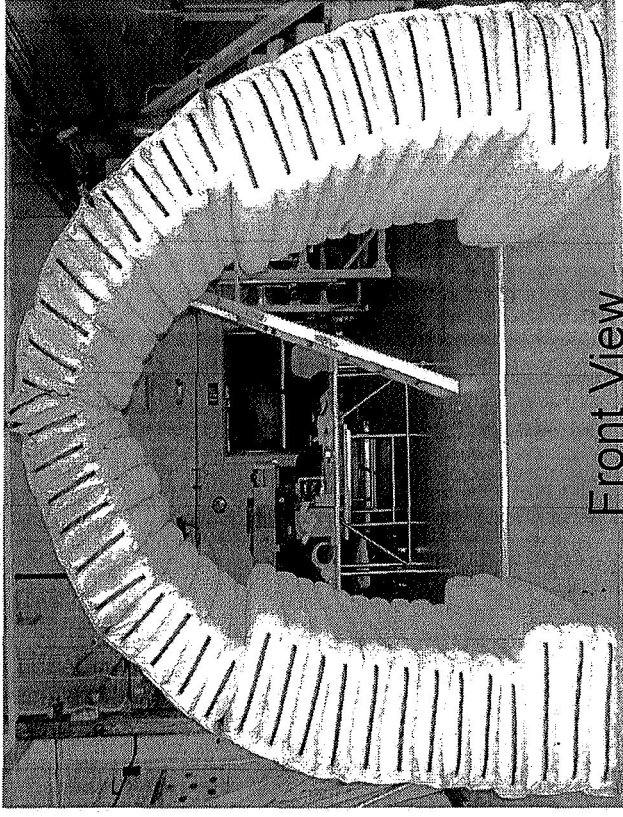




The Final Garage Structure



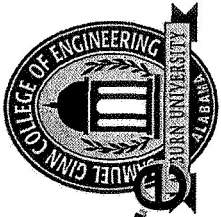
- Final Features
 - “Top-Connected” Kevlar
 - Bags hanging from a fabric layer, filled w/vermiculite
 - 3 bag sizes, 46 bags
 - 2’/1.5’/1’x6”x8’
 - Inside: ~8’ ht x 6’ wide
 - The Good Side (Right side in this view) has a relatively nice arch
 - Bags were slipping on the left side



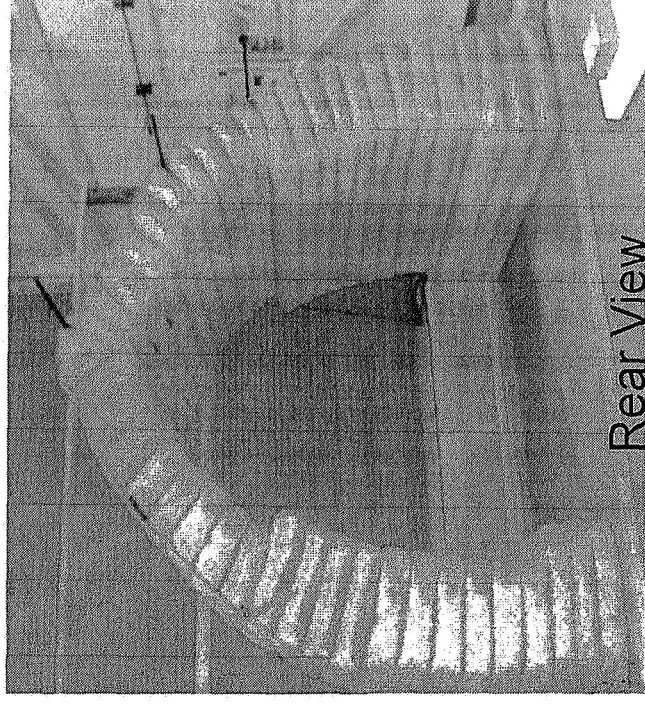
The Good Side



Comments on Final Garage Structure

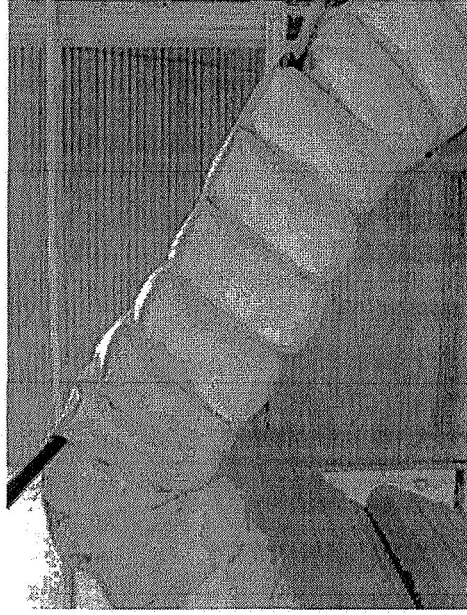
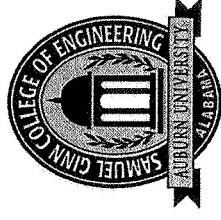


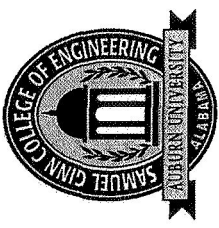
- Notice Pipe no longer supported.
- Sagging on right hand side in this view, but still a stable structure.
- Sagging here is a result of visible slipping. Bags were just not packed tight enough.





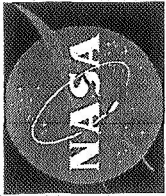
Observation of Bad Side





Conclusion

- The structure exhibits both good and bad packing, and the structural response of each.
- The structure stands, but is not as stable as it could have been if top 3 bags could have been filled tighter. This could have been corrected with a helical screw attached to a central shaft.
- Well packed bags are hard-to-the-touch, and can transmit compressive and shearing loads across the bag boundary and through the vermiculite.
- The top-connected bag structure was found advantageous in the erecting phase.
- Computational analysis, e.g. FEA, needs to be performed to aid the engineering of future designs.



Computer Simulation

